Sigurnost nuklearnih elektrana

Predavač:
Davor Grgić

Organizator:
IEEE PES i IEEE Student Branch Zagreb
Zagreb 2008

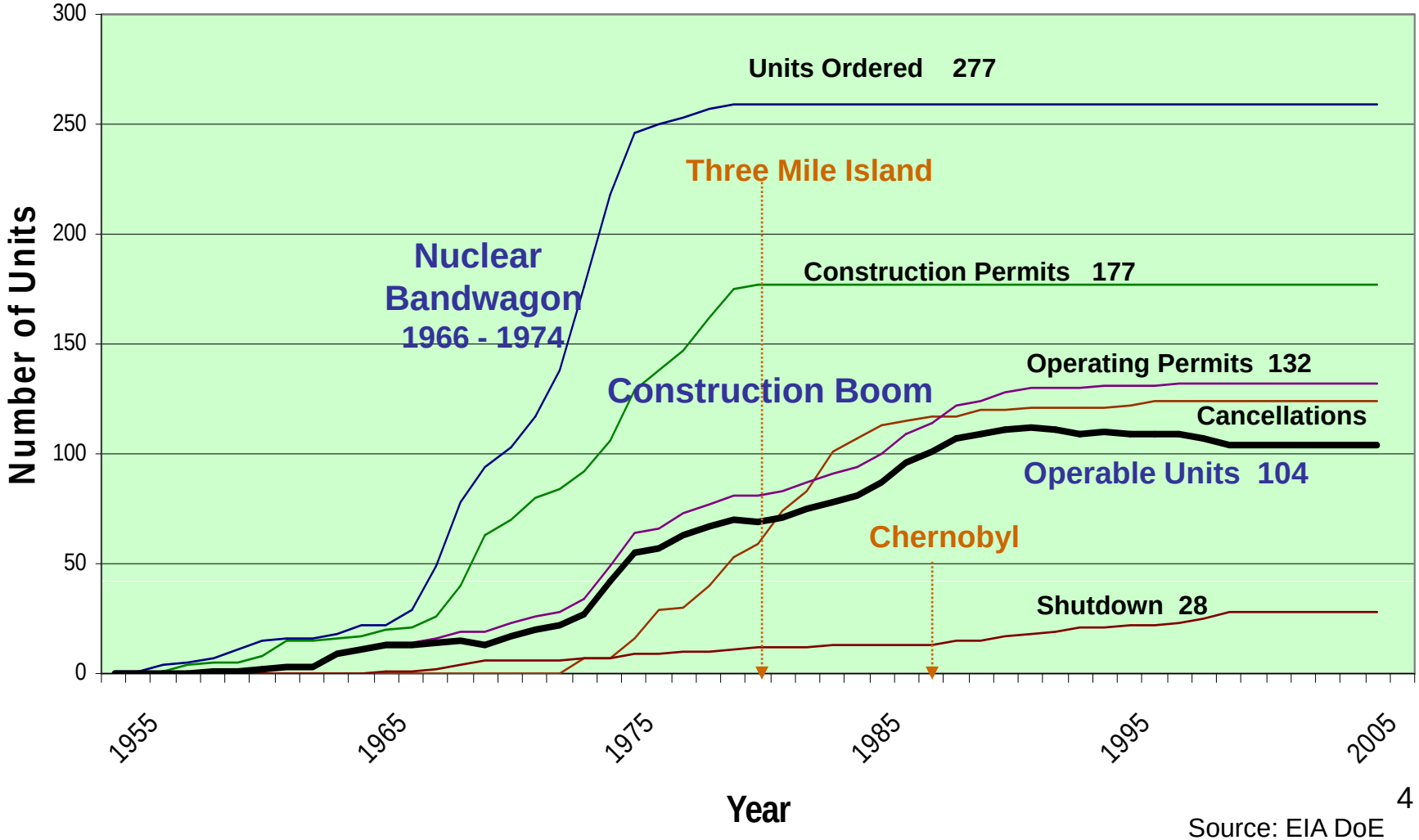
Da li su NE sigurne?

- Mogući odgovori:
  - Ne, to su tempirane atomske bombe
  - Da, produkt su suvremene tehnologije i svaka moguća nesreća je uzeta u obzir
  - Da, ali obzirom na prirodu procesa stanoviti rizik je prisutan
- U čemu je opasnost?
- Što je s drugim energetskim izvorima, da li se rizik isplati?
- Zašto zadnje vrijeme češće govorimo o nuklearnim elektranama?

Pod kojim uvjetima je rad nuklearnih elektrana prihvatljiv?

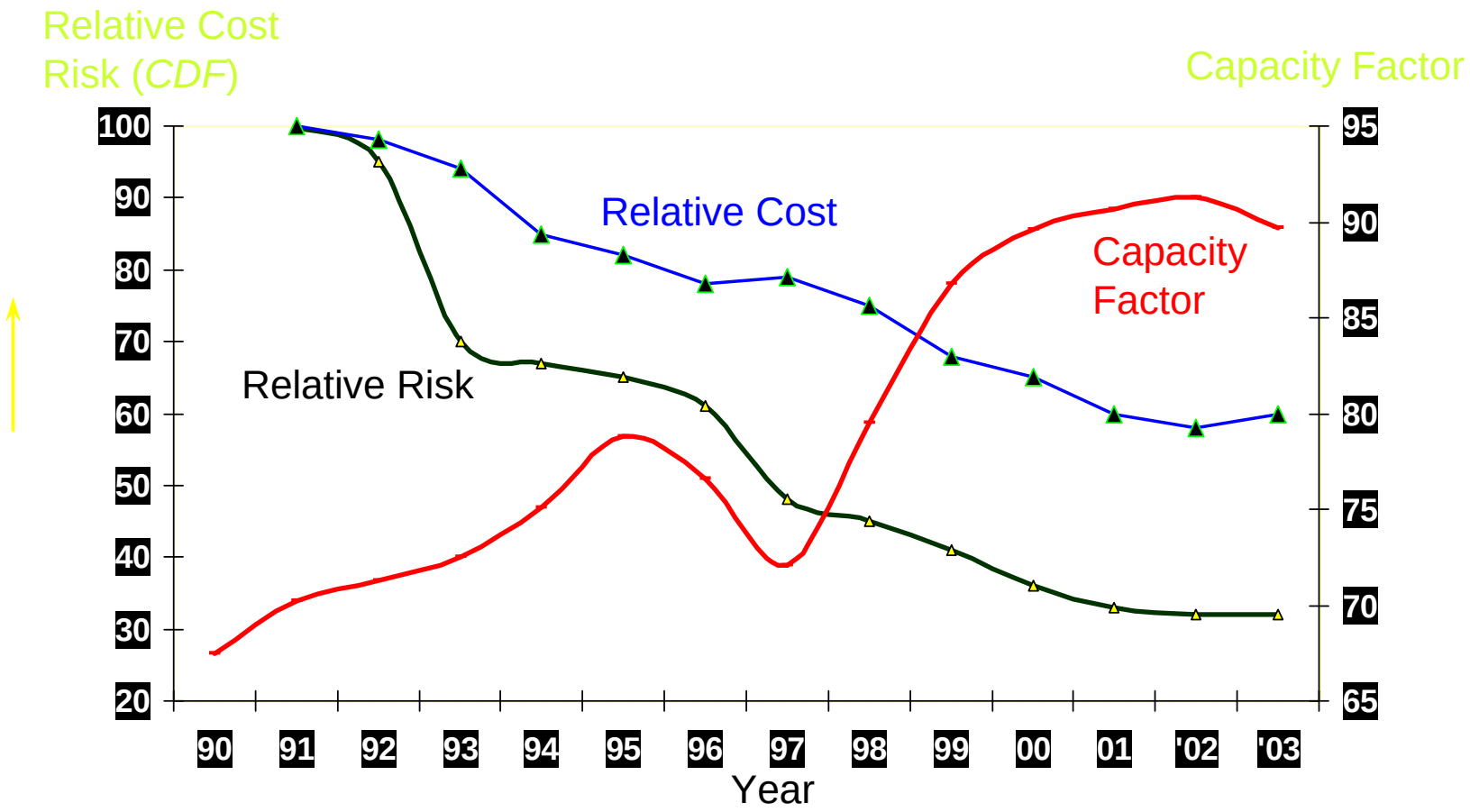
- NE moraju biti sigurne i pouzdane (nove generacije elektrana unapređuju ionako pouzdanu tehnologiju, ali se javlja problem terorizma)
- NE moraju biti konkurentne (porast cijene fosilnih goriva, njihova moguća nestašica, utjecaj na okoliš i eksterni troškovi zajedno s povećanom raspoloživošću kompenziraju velike investicijske troškove)
- Potrebno je riješiti problem istrošenog goriva (problem je tehnički rješiv i radi se na par demonstracijskih projekata, transmutacija bi mogla bitno popraviti situaciju)
- Spriječiti proliferaciju nuklearnog materijala (uglavnom političko pitanje i nije nužno vezano za energetsku primjenu)

Kako spomenuti faktori utječu na NE?
(Nuklearne elektrane u SAD 1953-2005)



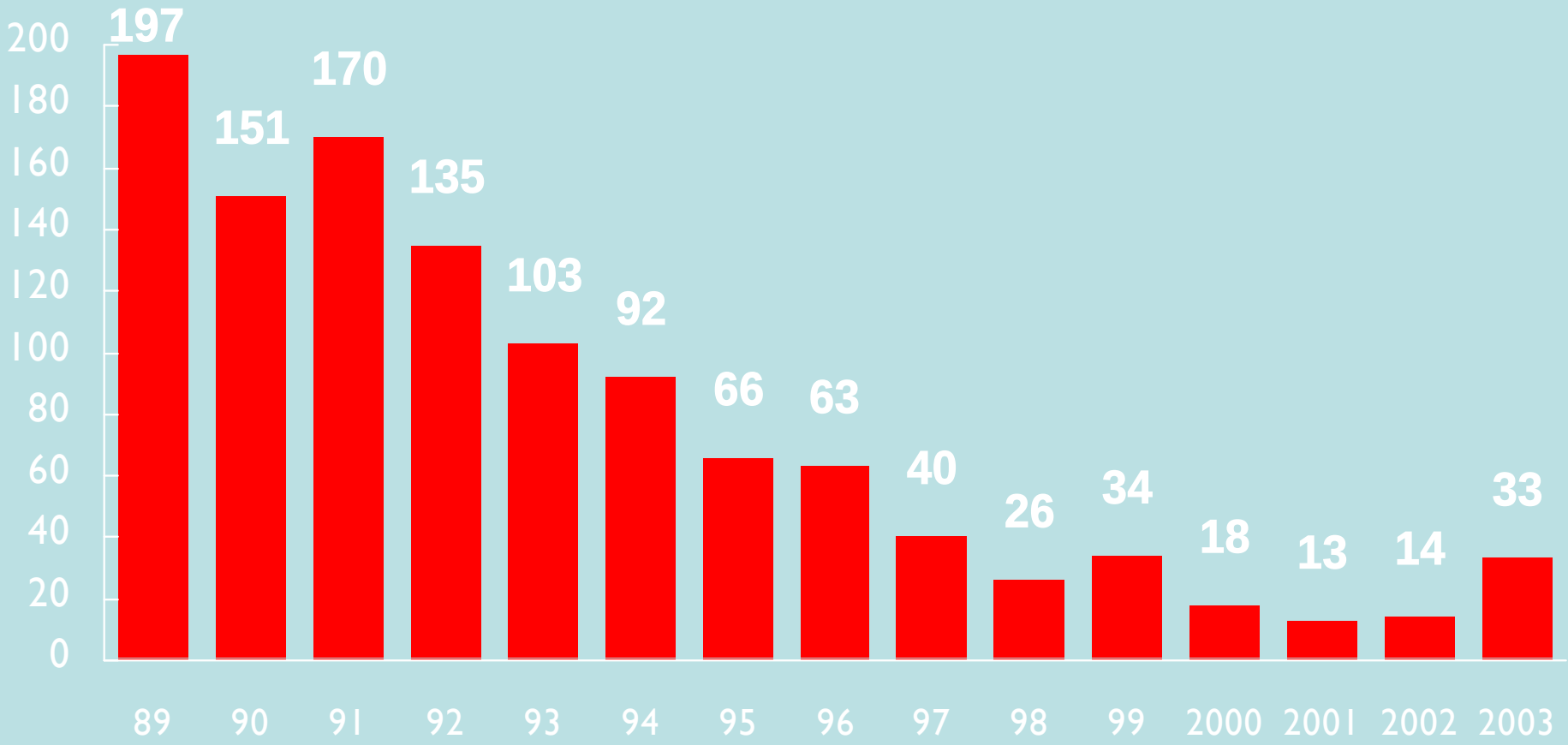
Source: EIA DoE

Sigurnost i isplativost NE u zadnjih 10 godina



Based on UDI, DOE & NUS Data plus info. from ERIN Eng & EPRI

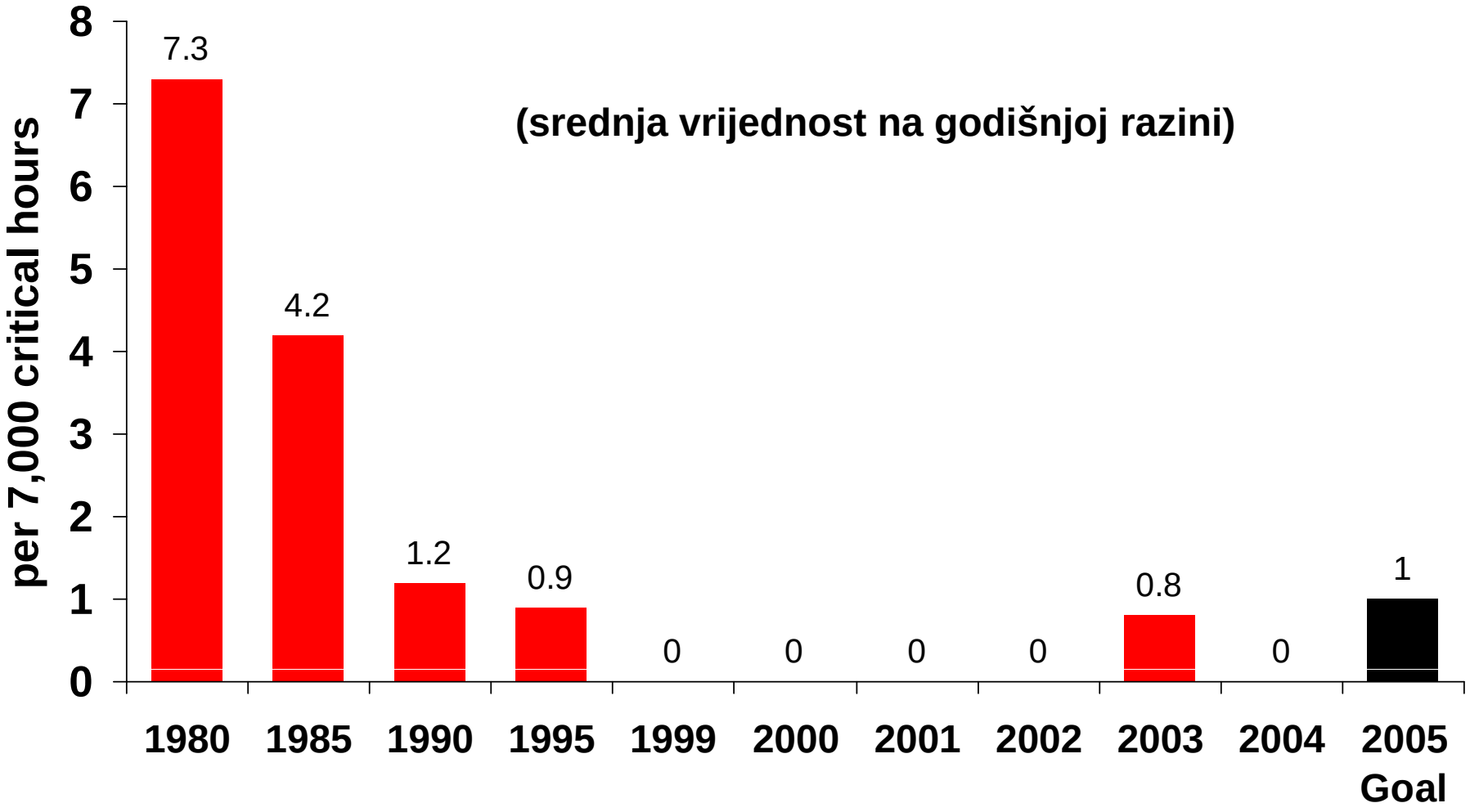
Broj neuobičajenih događaja prijavljen NRC (1989-2003)



Source: SCIENTECH · Updated 06/04

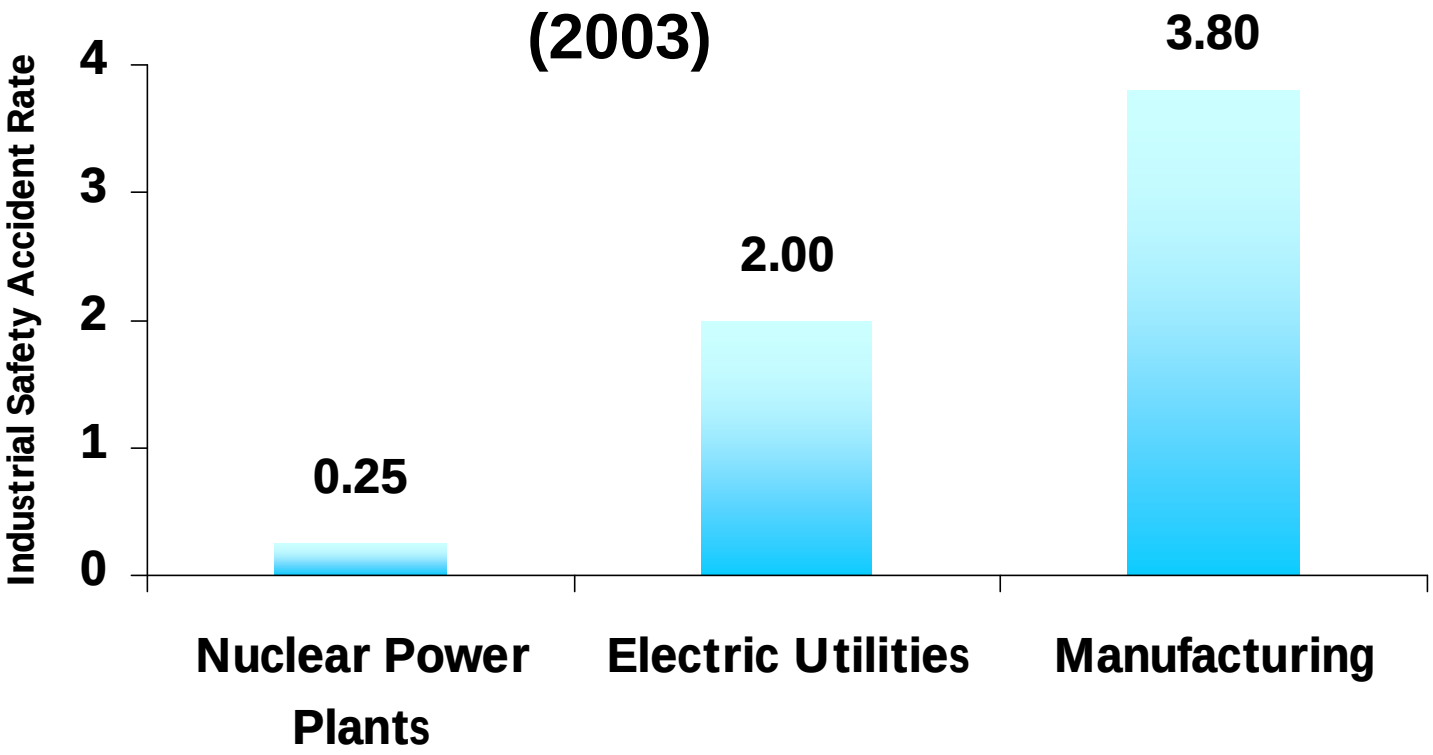
Note: A Notification of Unusual Event for power and non-power reactor licensees is a condition involving potential degradation of the level of plant safety that does not represent an immediate threat to public health and safety.

Broj neplaniranih brzih obustava



Source: WANO

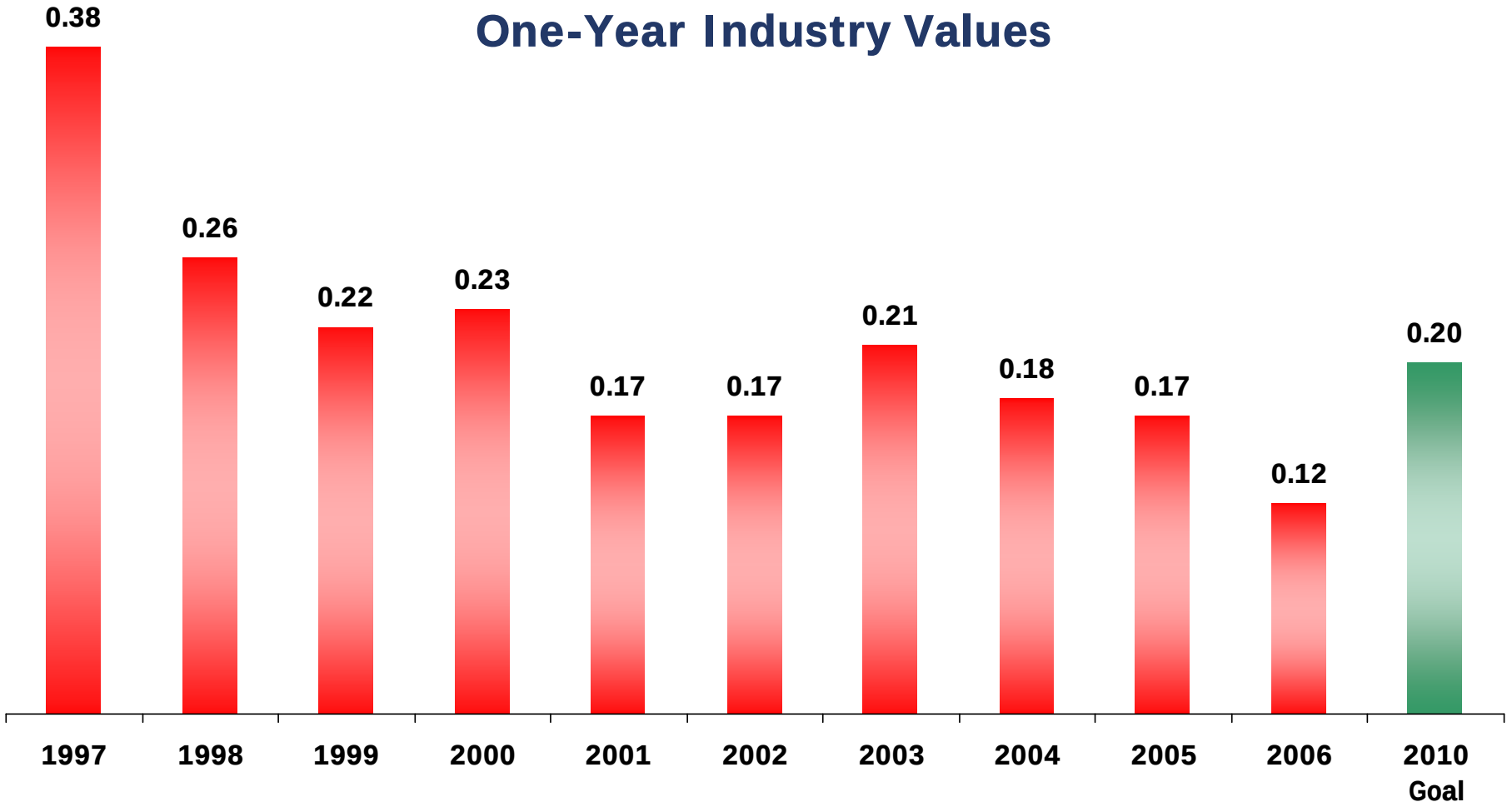
Broj industrijskih nesreća s nepovoljnim posljedicma na 200000 radnih sati



ISAR = number of accidents resulting in lost work, restricted work, or job transfer per 200,000 worker hours
Sources: Nuclear (World Association of Nuclear Operators), others (US Bureau of Labor Statistics). Data updated April 2005

U.S. Nuclear Industrial Safety Accident Rate

One-Year Industry Values



ISAR = Number of accidents resulting in lost work, restricted work, or fatalities per 200,000 worker hours.

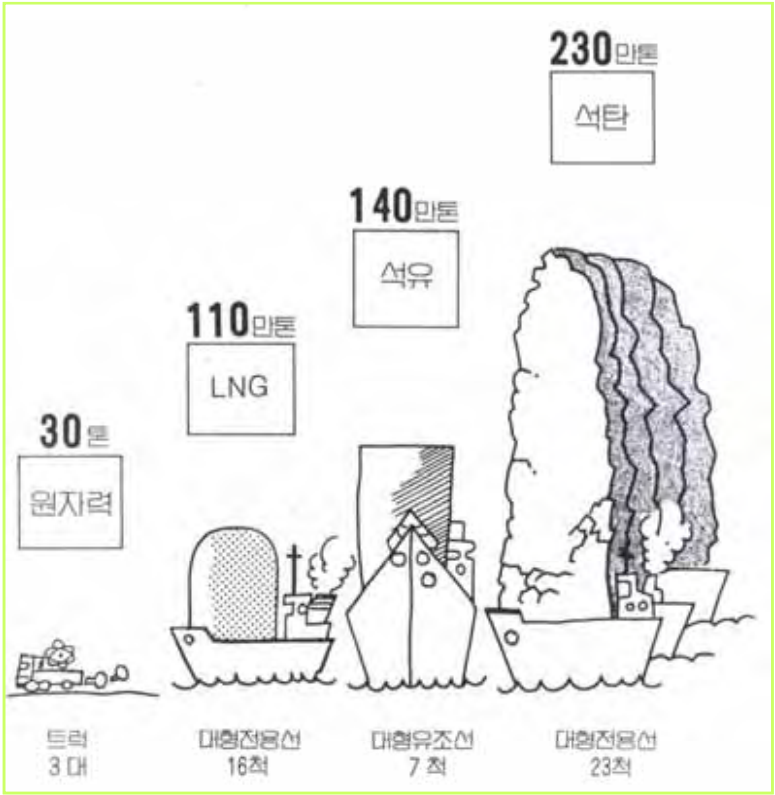
Source: World Association of Nuclear Operators
Updated: 4/07

Environmental effects of fossil fuels compared to nuclear

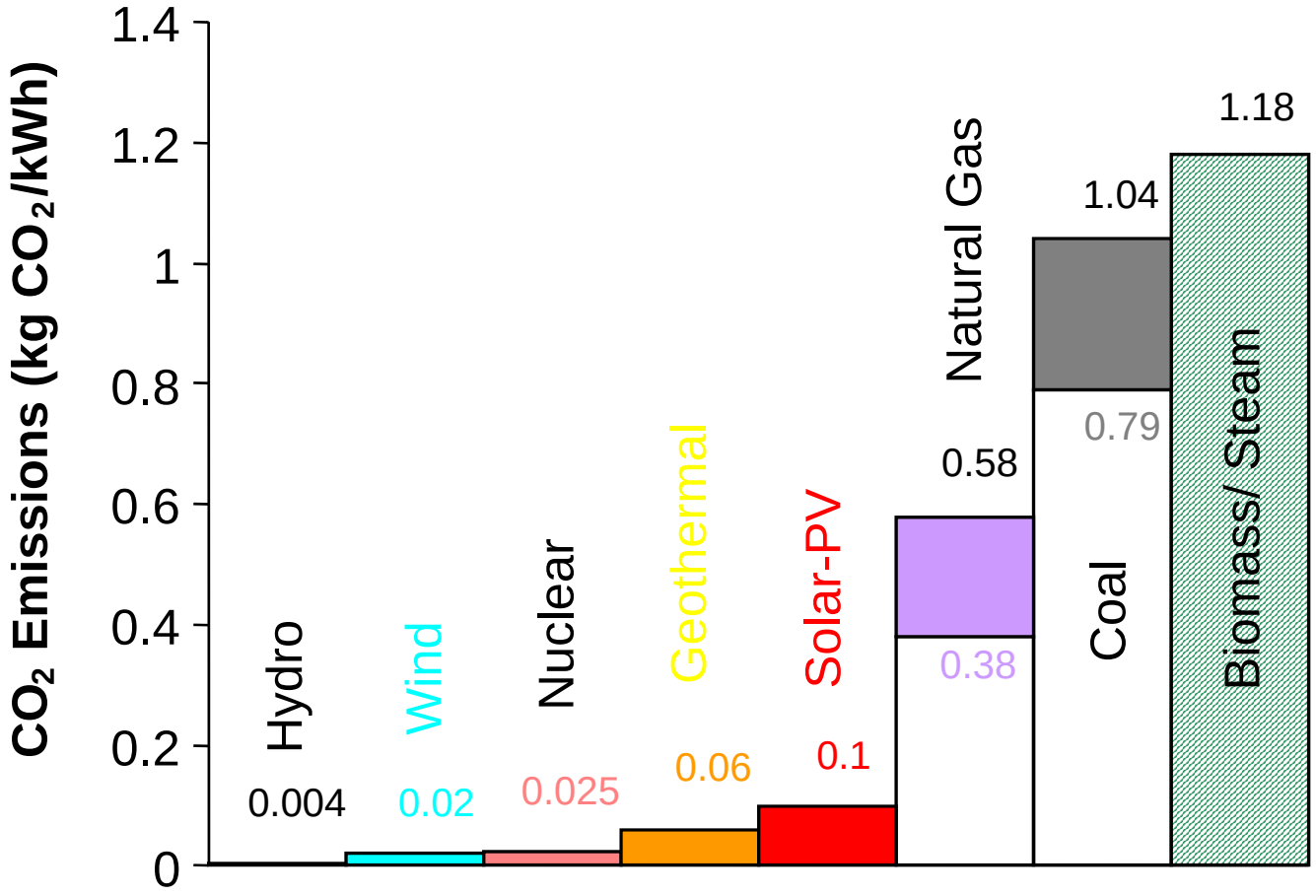
- ***Fossil fuels***
  - Global climate change
  - Air quality degradation (coal, oil)
  - Lake acidification and forest damage (coal, oil)
  - Toxic waste contamination (coal ash and slag, abatement residues)
  - Groundwater contamination
  - Marine and coastal pollution (oil)
  - Land disturbance
  - Large fuel and transport requirements
  - Resource depletion
- ***Nuclear (full energy chain)***
  - Severe reactor accident release
  - Waste repository release
- ***Hydroelectric***
  - Population displacement
  - Land loss and change in use
  - Ecosystem changes and health effects
  - Loss of biodiversity
  - Dam failure
  - Decommissioning
- ***Renewables (solar, wind, geothermal, biomass)***
  - Air quality degradation (geothermal, biomass)
  - Extensive land use
  - Ecosystem changes
  - Fabrication impact (solar photovoltaic cells)
  - Noise pollution (wind)

Potrošnja goriva u NE i TE

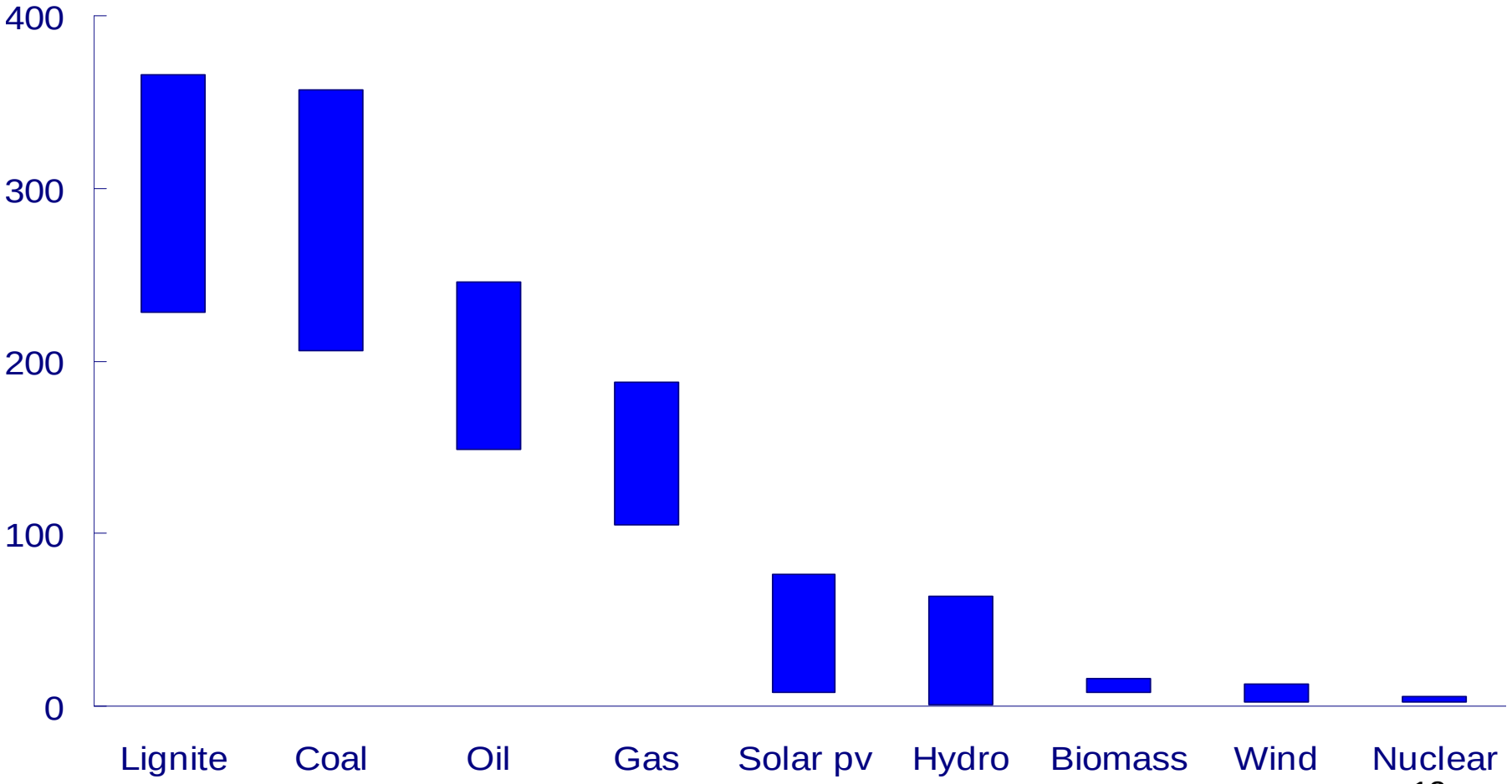
- Needed Fuel for operation of 1,000MWe power plant:
  - Nuclear Power Plant : 30 Ton
    - Truk : 3
  - Gas Power Plant : 1.1 M Ton
    - Liquid Gas Ship : 16
  - Oil Power Plant : 1.4 M Ton
    - Big Oil Tanker Ship : 7
  - Coal Power Plant : 2.3 M Ton
    - Big Coal transportation Ship : 23



CARBON DIOXIDE EMISSIONS
Construction/Operation/Fuel Preparation
(kg CO_2 / kWh)

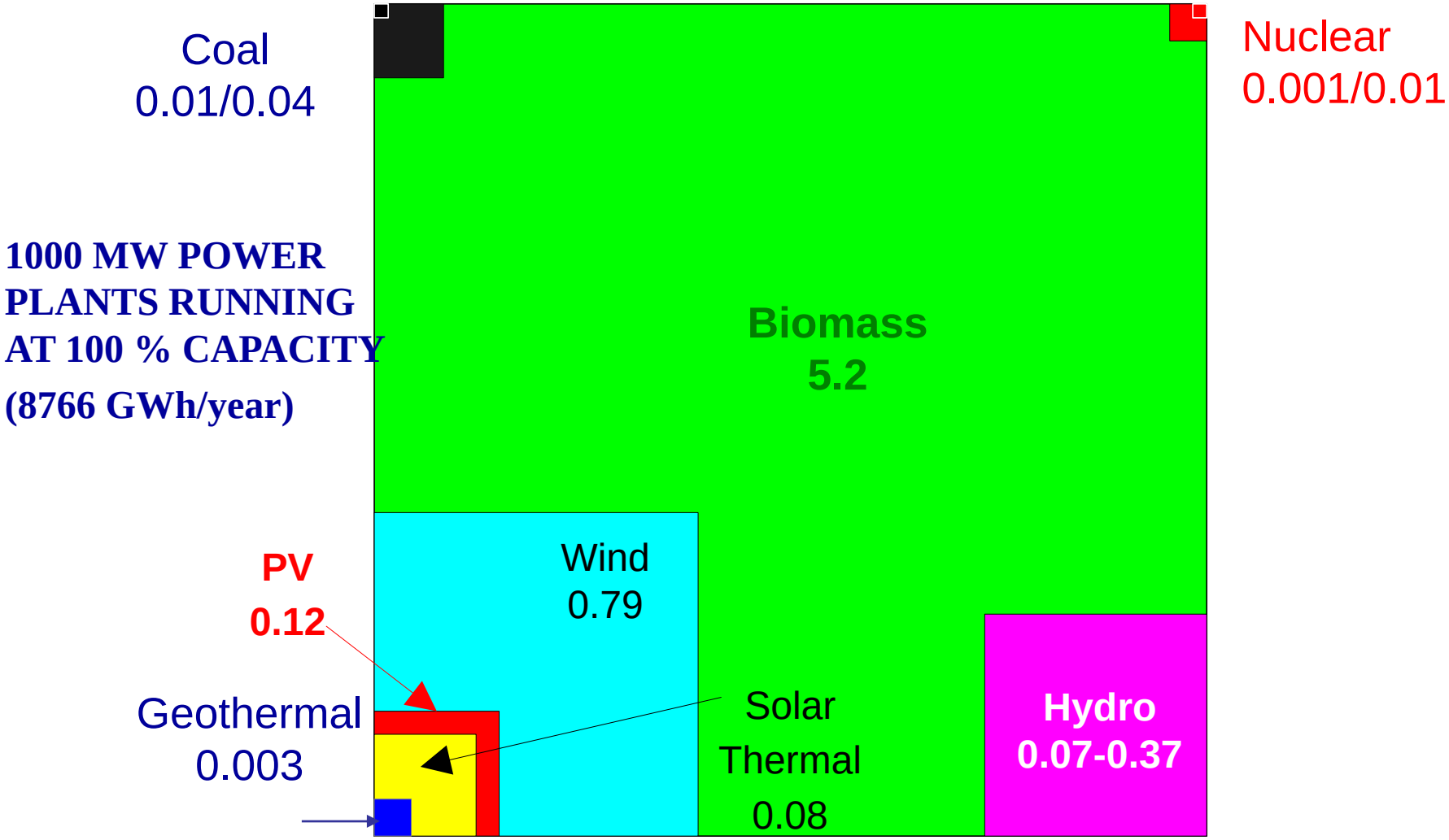


Greenhouse Gas Emissions from Electricity Production Chains (gCO_2 equiv./kWh)



Power Plant Land Use Required (km^2 / MW)

Source: J. Davidson (2000)



Zauzeće zemljišta za elektranu od 1000 MWe

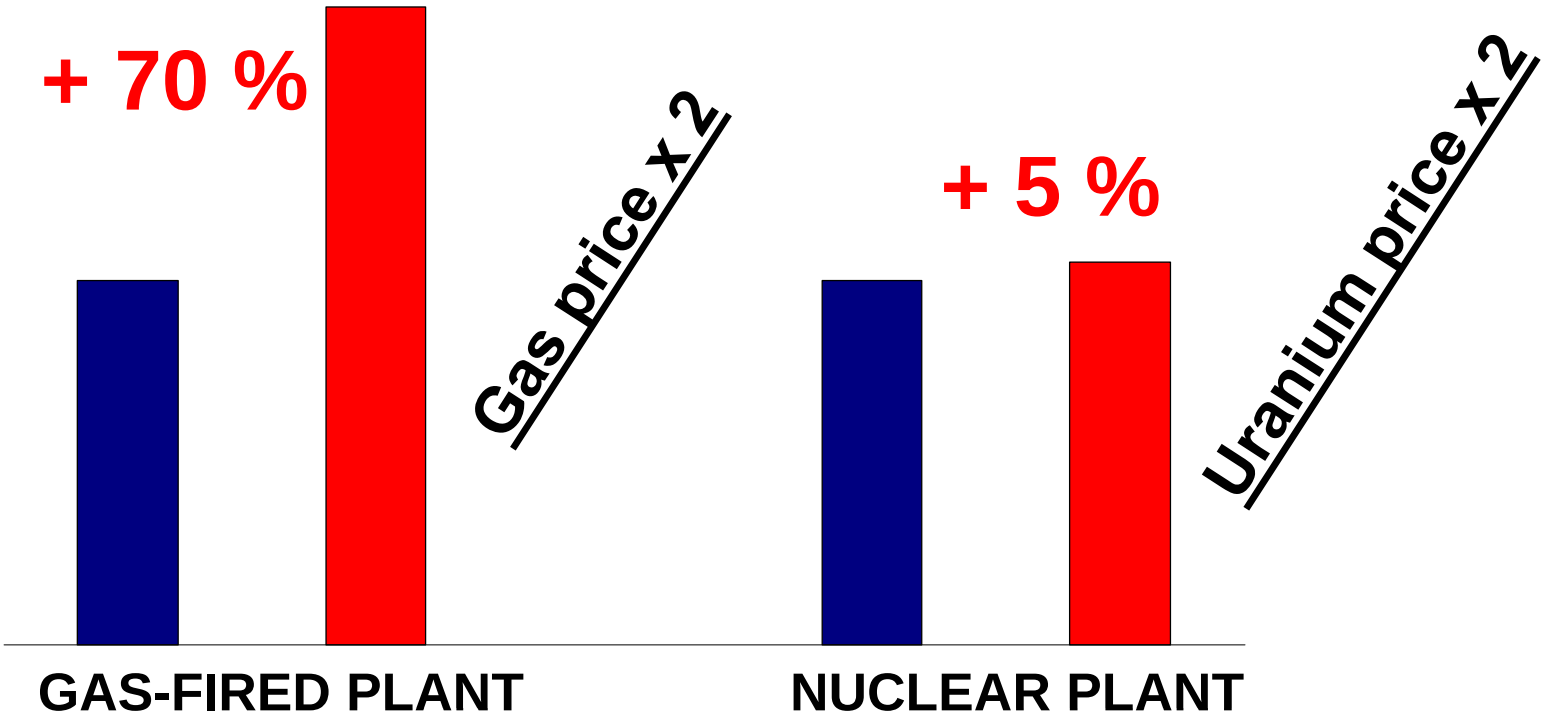
Fossil and nuclear sites:	**1–4 km^2**
Solar thermal or photovoltaic (PV) parks: (a small city)	**20–50 km^2**
Wind *fields*:	**50–150 km^2**
Biomass *plantations*:	**4000–6000 km^2**

Materijali potrebni za gradnju

- Nuclear:1970’s vintage PWR, 90% capacity factor, 60 year life
  - –40 MT steel / MW(average)
  - –190 m3 concrete / MW(average)
- Wind:1990’s vintage, 6.4 m/s average wind speed, 25% capacity factor, 15 year life
  - –460 MT steel / MW (average)
  - –870 m3 concrete / MW(average)
- Coal:78% capacity factor, 30 year life
  - –98 MT steel / MW(average)
  - –160 m3 concrete / MW(average)
- Natural Gas Combined Cycle:75% capacity factor, 30 year life
  - –3.3 MT steel / MW(average)
  - –27 m3 concrete / MW(average)

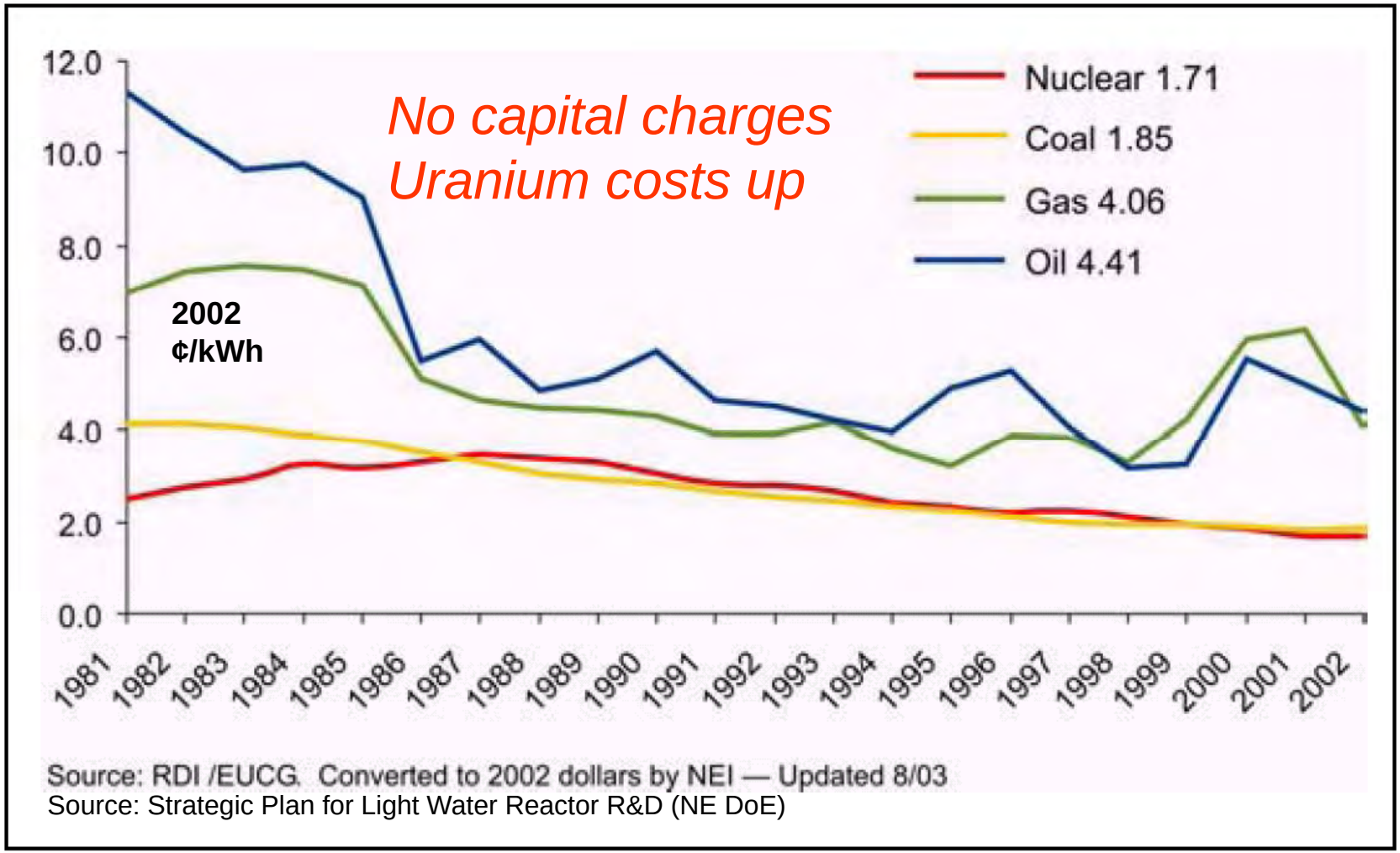
Concrete + steel are >95% of construction inputs

Osjetljivost cijene el. energije na promjenu cijene goriva



Troškovi proizvodnje električne energije u SAD

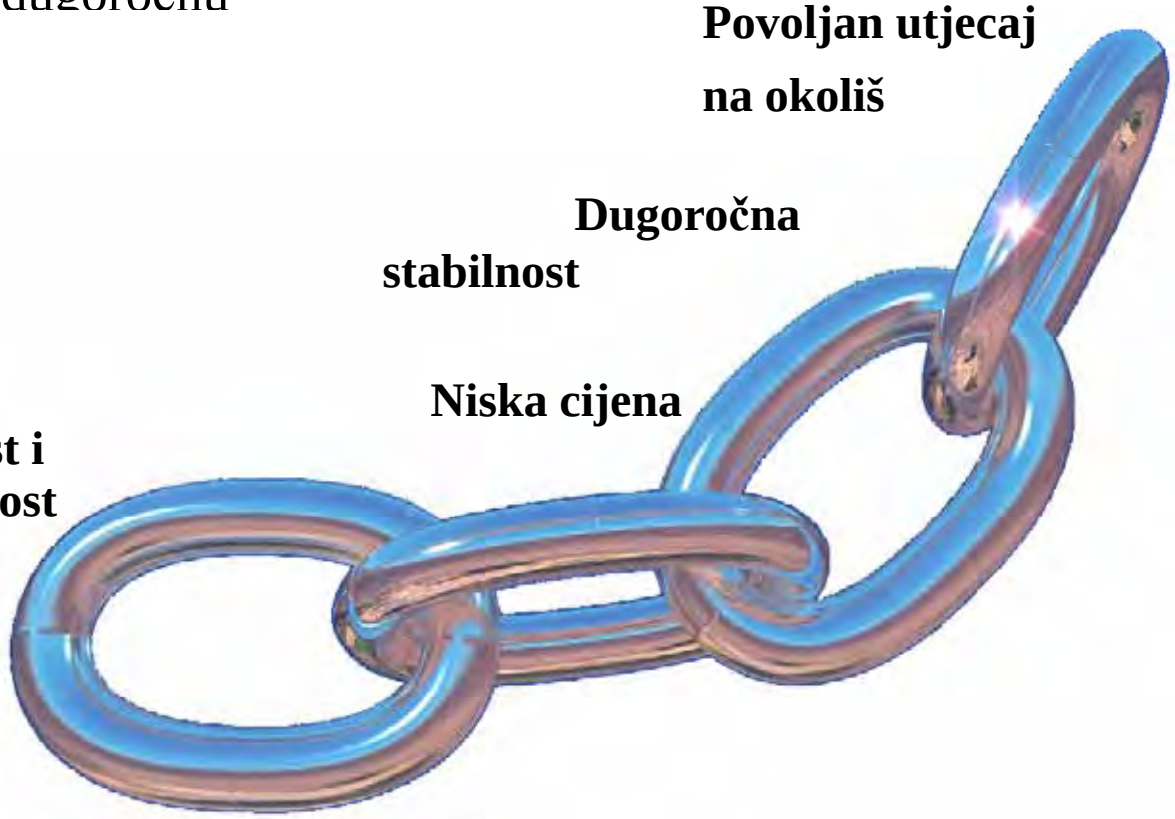
Operations, Maintenance and Fuel



Source: Strategic Plan for Light Water Reactor R&D (NE DoE)

Da li nuklearne elektrane imaju budućnost?

Da, ako nastave biti sigurne i pouzdane uz nisku proizvodnu cijenu električne energije i ako demonstriraju dugoročnu stabilnost za ulaganje i neov
cijena goriva.
Za razliku od fosilnih tehnol
za zaštitu okoliša, razgradnj
su uzeti u obzir.



Nuklearni i klasični energetski izvori

Deaths from Accidents from Generating Electricity per Billion MWe-hr

*Includes Chernobyl

400-page study of 4,290 energy-related accidents: 15,000 deaths related to oil, 8,000 related to coal, 5,000 related to gas.

Paul Scherrer Institute, Switzerland, 2001

Some energy-related accidents since 1977

Place	year	number killed	comments
Machhu II, India	1979	2500	hydro-electric dam failure
Hirakud, India	1980	1000	hydro-electric dam failure
Ortuella, Spain	1980	70	gas explosion
Donbass, Ukraine	1980	68	coal mine methane explosion
Israel	1982	89	gas explosion
Guavio, Colombia	1983	160	hydro-electric dam failure
Nile R, Egypt	1983	317	LPG explosion
Cubatao, Brazil	1984	508	oil fire
Mexico City	1984	498	LPG explosion
Tbilisi, Russia	1984	100	gas explosion
northern Taiwan	1984	314	3 coal mine accidents

Some energy-related accidents since 1977

Chernobyl, Ukraine	1986	31+	nuclear reactor accident
Piper Alpha, North Sea	1988	167	explosion of offshore oil platform
Asha-ufa, Siberia	1989	600	LPG pipeline leak and fire
Dobrnja, Yugoslavia	1990	178	coal mine
Hongton, Shanxi, China	1991	147	coal mine
Belci, Romania	1991	116	hydro-electric dam failure
Kozlu, Turkey	1992	272	coal mine methane explosion
Cuenca, Equador	1993	200	coal mine
Durunkha, Egypt	1994	580	fuel depot hit by lightning
Seoul, S.Korea	1994	500	oil fire
Minanao, Philippines	1994	90	coal mine
Dhanbad, India	1995	70	coal mine

Some energy-related accidents since 1977

Taegu, S.Korea	1995	100	oil & gas explosion
Spitsbergen, Russia	1996	141	coal mine
Henan, China	1996	84	coal mine methane explosion
Datong, China	1996	114	coal mine methane explosion
Henan, China	1997	89	coal mine methane explosion
Fushun, China	1997	68	coal mine methane explosion
Kuzbass, Siberia	1997	67	coal mine methane explosion
Huainan, China	1997	89	coal mine methane explosion
Huainan, China	1997	45	coal mine methane explosion
Guizhou, China	1997	43	coal mine methane explosion
Donbass, Ukraine	1998	63	coal mine methane explosion
Liaoning, China	1998	71	coal mine methane explosion

Some energy-related accidents since 1977

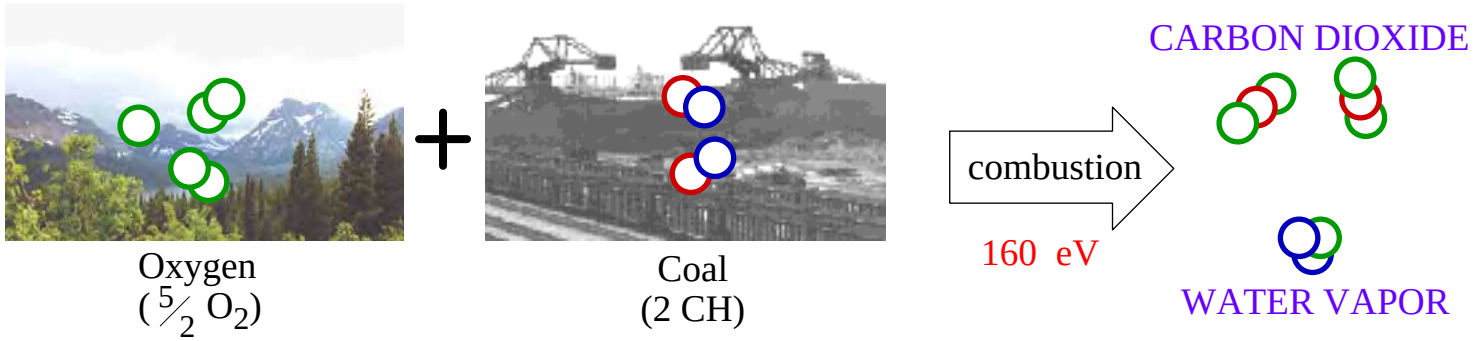
Warri, Nigeria	1998	500+	oil pipeline leak and fire
Donbass, Ukraine	1999	50+	coal mine methane explosion
Donbass, Ukraine	2000	80	coal mine methane explosion
Shanxi, China	2000	40	coal mine methane explosion
Guizhou, China	2000	150	coal mine methane explosion
Shanxi, China	2001	38	coal mine methane explosion
Sichuan, China	2002	23	coal mine methane explosion
Jixi, China	2002	115	coal mine methane explosion

Comparison of accident statistics in primary energy production

Fuel	Immediate fatalities 1970-92	Who?	Deaths per TWy* electricity
Coal	6400	workers	342
Natural gas	1200	workers & public	85
Hydro	4000	public	883
Nuclear	31	workers	8

Electricity generation accounts for about 40% of total primary energy

Energija iz fosilnih goriva



- **Fossil Fuel (Coal) Energy Density: 2.9 x 10^7 J/kg**
- **Fuel Consumed by 1000-MW_e Plant: 7,300,000 kg/day**
- **Waste:**

Coal Combustion Products

NO_x → High temperature combustion

SO_x → Sulfur in coal (0.4% - 5%)

Ash → (5% - 25% of coal mass)

CO_2 → Global warming

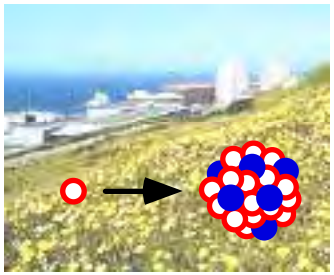
Mining

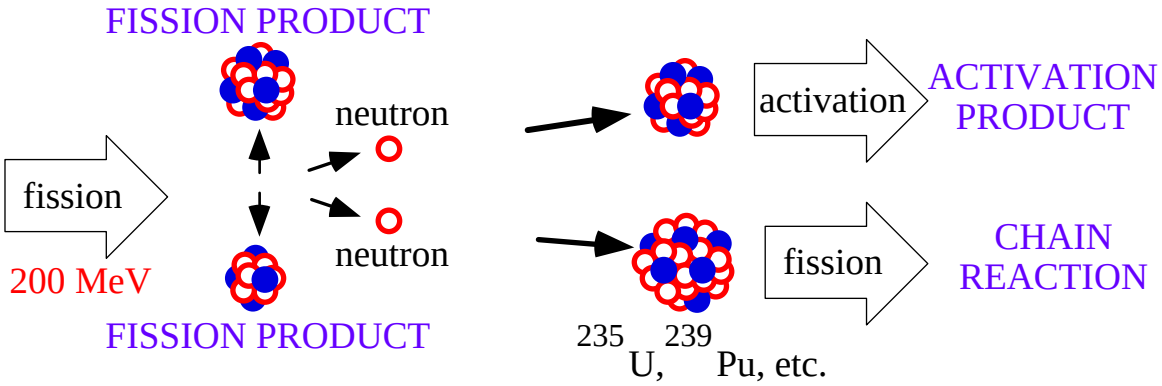
Leachates/ dust from mining

Construction materials

1999 Global Coal Consumption: 3 billion tons

Energija nuklearne fisije

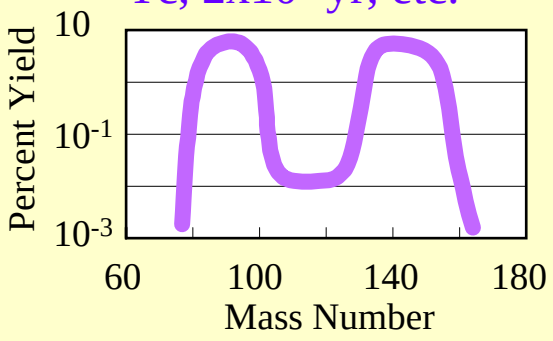




- **Fission Fuel Energy Density: 8.2 x 10^{13} J/kg (20,000 t_{HE}/kg)**
- **Fuel Consumed by 1000-MW_e Plant: 3.2 kg/day**
- **Waste:**

Fission Prod. (3.2 kg/day)

^{90}Sr, 30 yr; ^{137}Cs, 30 yr; ^{99}Tc, 2x10^5 yr; etc.



Activation Products

Fuel → Transuranics, longer half lives (^{239}Pu, 24,000 yr; ^{237}Np, 2x10^6 yr; etc.)

Structures → Moderate half lives, low-level waste (^{60}Co, 5 yr)

Coolants → Low (water) to moderate (metals) half lives

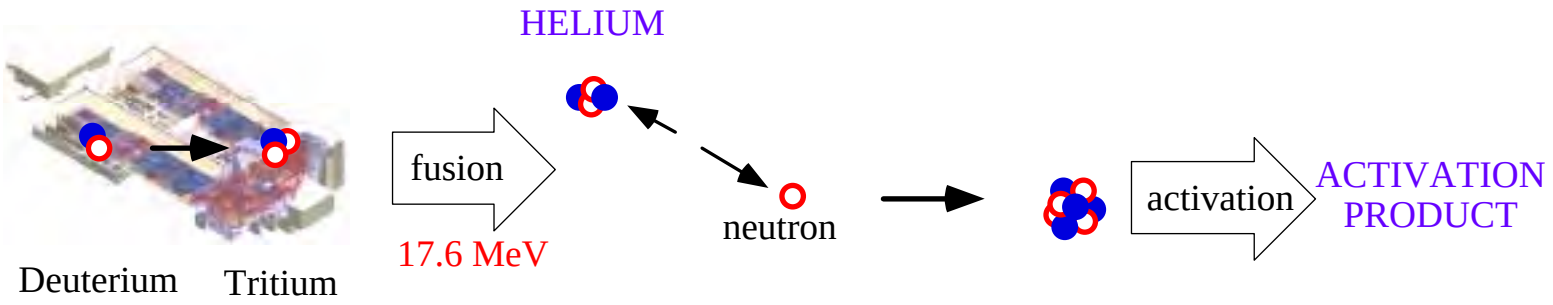
Transmutation → Convert from long to short half life

Mining

Radon from mill tails if not capped

Construction materials

Energija nuklearne fuzije



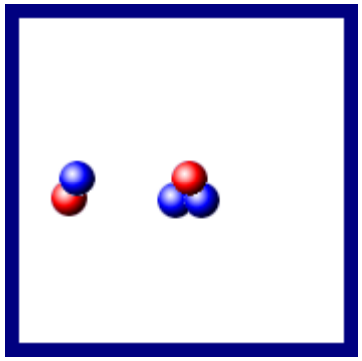
- **Fusion Fuel Energy Density: 3.4 x 10^{14} J/kg**
- **Fuel Consumed by 1000-MW_e Plant: 0.6 kg/day**
- **Waste:**

Activation Products			Mining
Structures	→	Moderate half lives, depends strongly on material selection (low atomic mass better)	Construction materials
Coolants	→	Short half lives (low atomic mass)	
Blanket	→	$n + {}^{6}Li \rightarrow 4He + T$ $n + {}^{m}M \rightarrow 2n + {}^{m-1}M$	

Energija iz atomske jezgre

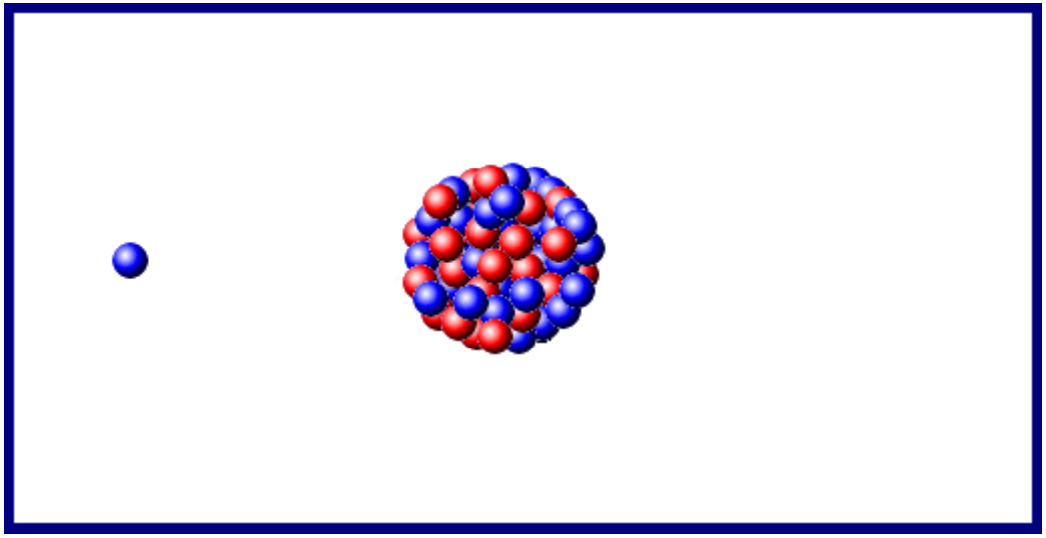
Fuzija

Spajanje manjih jezgri u veću

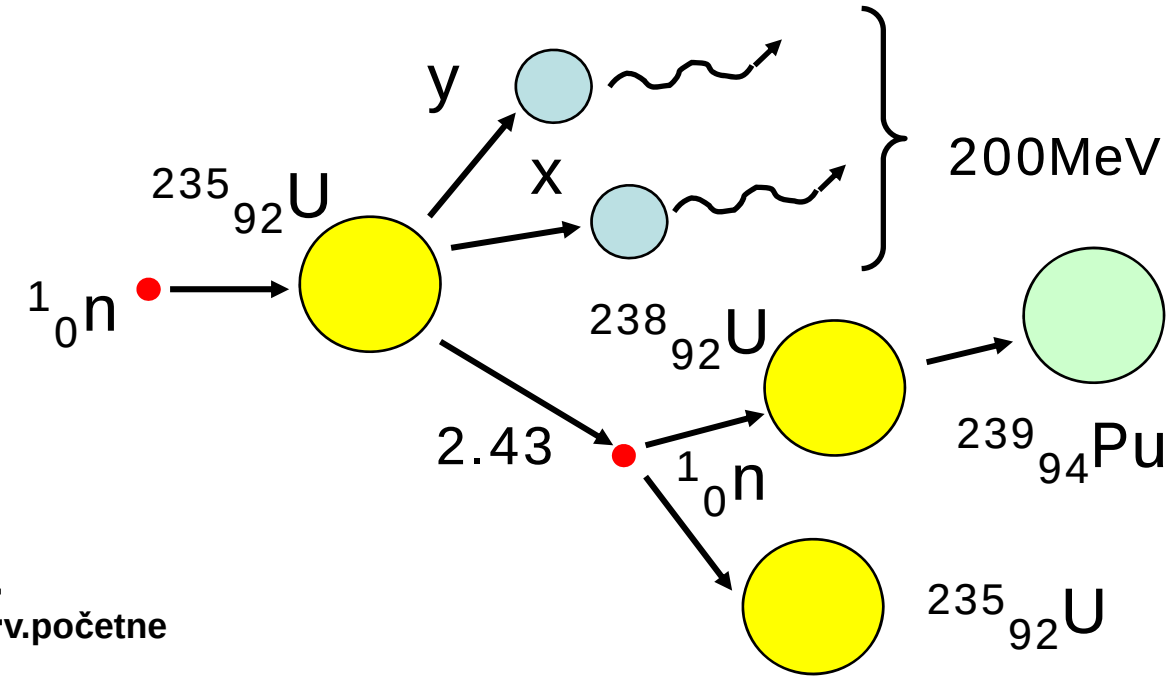


Fisija

Raspad teških jezgri na lakše



Fisija Urana



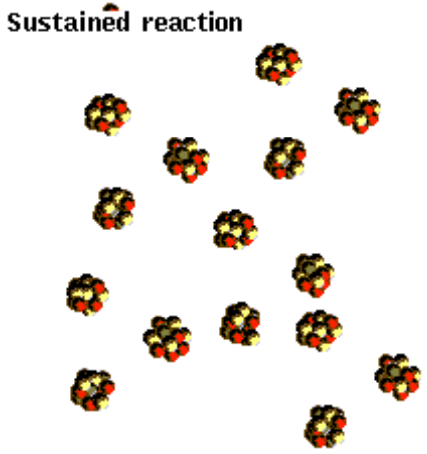
Fisija: $\Delta E_{vezanja} > E_{aktivacije}$

$\Delta E_{vezanja.jezgre} = E_{v.nastale} - E_{v.početne}$

$E_{aktivacije}$ = potrebna energija za fisiju

U235 – fisibilan
U238 – fisibilan s pragom

1 eV = 1,60219E-19 J
200 Mev = 3,204E-11 J
1 W = 3,124E10 fisija

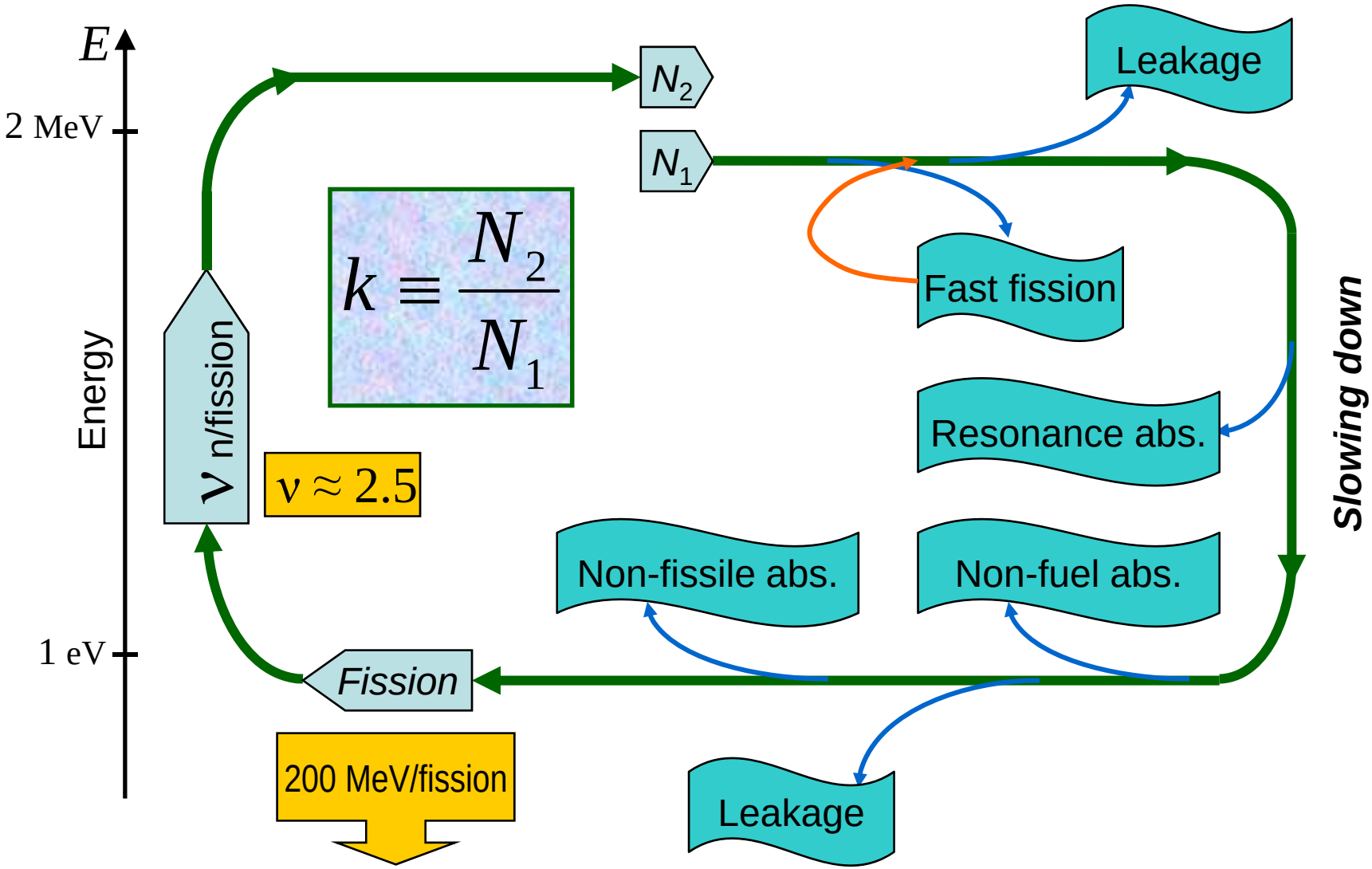


Energija iz fisije	
Kinetička fragmenata	83.5%
Trenutne γ-zrake	2.5%
Kinetička neutrona	2.5%
β-raspad fragmenata	3.5%
γ zrake fragmenata	3.0%
Energija neutrina	5.0%

Nuklearni reaktor

- Nuklearni reaktor je sustav projektiran da omogući kontroliranu samoodržavajuću nuklearnu reakciju fisije
- Parametar koji opisuje tijek odvijanja procesa naziva se multiplikacijski faktor k.
- Definiran je kao omjer srednjeg broja neutrona u dvije susjedne generacije neutrona (prije i poslije fisije)
- Da bi se nuklearna reakcija mogla nadzirati njegova vrijednost ne smije biti puno veća od 1
- Reaktor koji ima k=1 zovemo kritičnim reaktorom i on održava konstantan broj neutrona i snagu proizvedenu fisijom
- Ako je k<1 broj neutrona i snaga reaktora će se s vremenom smanjivati i reaktor zovemo podkritičnim a ako je k>1 broj neutrona u reaktoru i snaga reaktora će se povećavati i reaktor zovemo nadkritičnim
- Kako je k u praksi vrlo blizu 1 uvedena je veličina koja se naziva reaktivnost i definirana je kao $\rho=(k-1)/k$ i predstavlja relativno odstupanje reaktora od kritičnog stanja

Ciklus neutrona u reaktoru

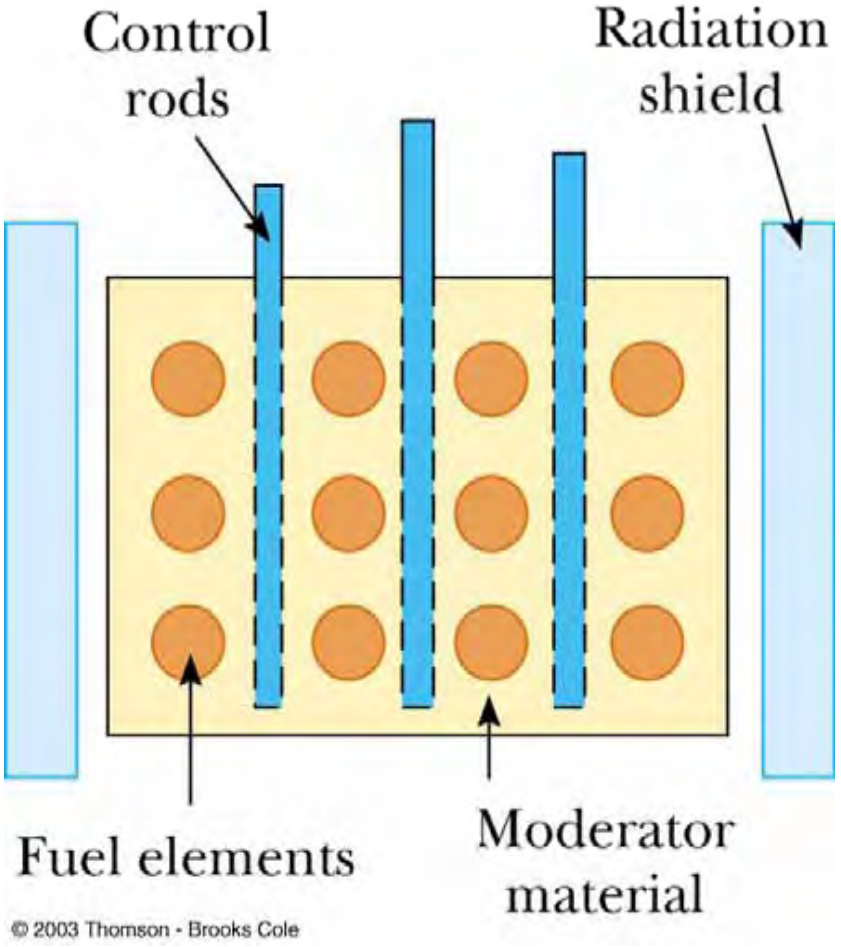


Ciklus neutrona u reaktoru

- Neutroni su unutar reaktora podvrgnuti procesu difuzije (struje od mjesta veće gustoće prema mjestu niže gustoće)
- Za kritičnost reaktora bitne su dvije vrste neutrona
- Promptni neutroni nastaju direktno pri fisiji
- Zakašnjeli neutroni su rezultata raspada fisijskih produkata
- Udjel zakašnjelih neutrona u ukupnom broju neutrona je od 0.22% do 0.65%
- Najveći broj zakašnjelih neutrona se pojavi unutar 70 s nakon procesa fisije
- Zakašnjeli neutroni su bitni za kontrolu reaktora

Osnovni izgled reaktora

- Nuklearno gorivo je organizirano u gorivne elemente
- Moderator je materijal koji ima sposobnost usporavanja neutrona
- Rashladno sredstvo odvodi toplinu iz reaktora
- Posebni kontrolni elementi napravljeni od materijala koji absorbiraju neutrone služe za nadzor broja neutrona raspoloživih za fisiju
- Nuklearno gorivo, moderator, rashladno sredstvo i kontrolni element čine jezgru reaktora
- Jezgra je okružena štitom od zračenja



Tipovi reaktora

- **Reaktori se mogu podijeliti:**
  - **prema tipu goriva**
  - **korištenom hladiocu (rashladnom sredstvu)**
  - **potrebi za usporavanje neutrona**
    - **brzi reaktori**
    - **termički reaktori (tip moderatora)**
  - **namjeni reaktora**
    - **istraživački reaktori,**
    - **proizvodnja električne energije i/ili topline,**
    - **proizvodnja nuklearnog materijala**
    - **proizvodnja vodika**
    - **desalinizacija**

- **Da se osigura lančana reakcija potrebno je:**
  - **imati odgovarajuću količinu goriva**
  - **ograničiti apsorpciju neutrona**
  - **ograničiti bijeg neutrona (kritične dimenzije reaktora i reflektor)**

Ostatna toplina

Generirana snaga
nakon obustave reaktora:

- **ostatna toplina posljedica je**

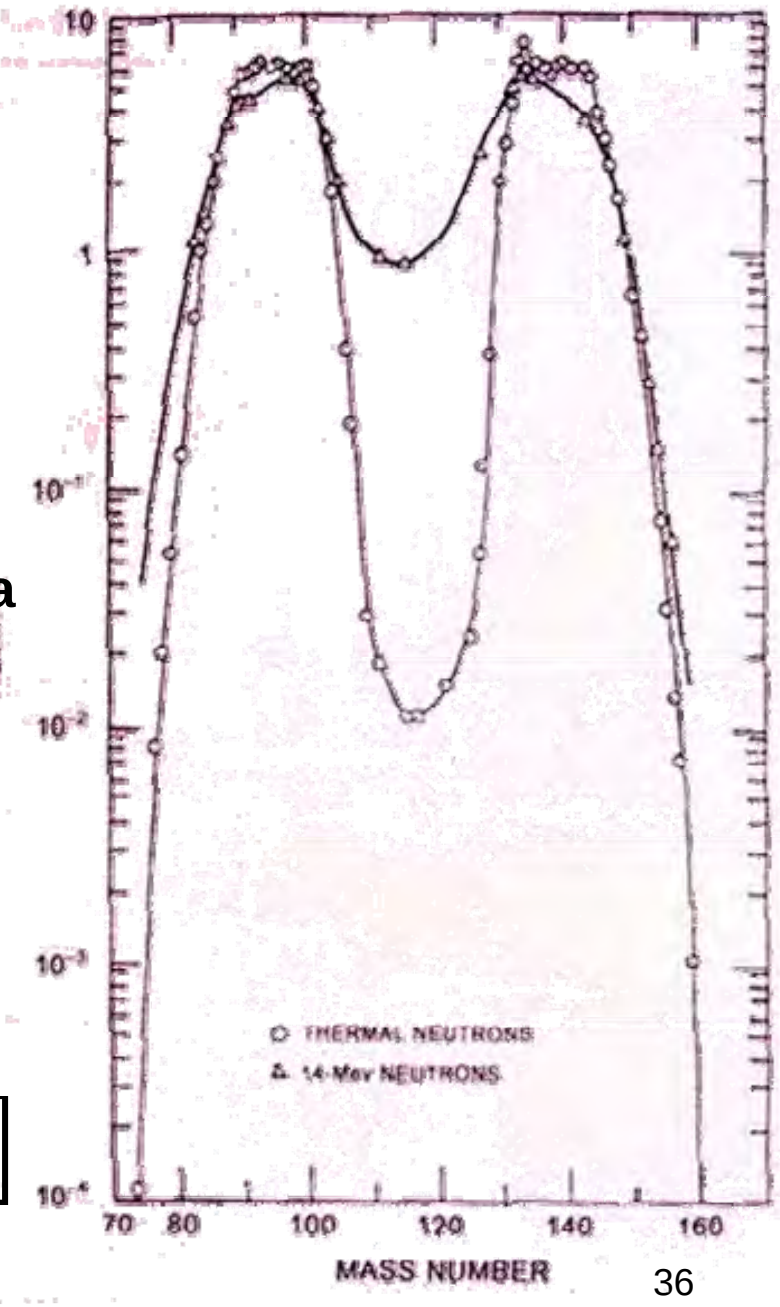
radioaktivnog raspada fisijskih produkata

P_0 – snaga reaktora prije obustave

t_0 – vrijeme rada reaktora
t – vrijeme rada i obustave

(vremena su u danima)

$$P = P_0 \cdot 0{,}0061 \cdot \left[(t - t_0)^{-0,2} - t^{-0,2} \right]$$



Ostatna toplina

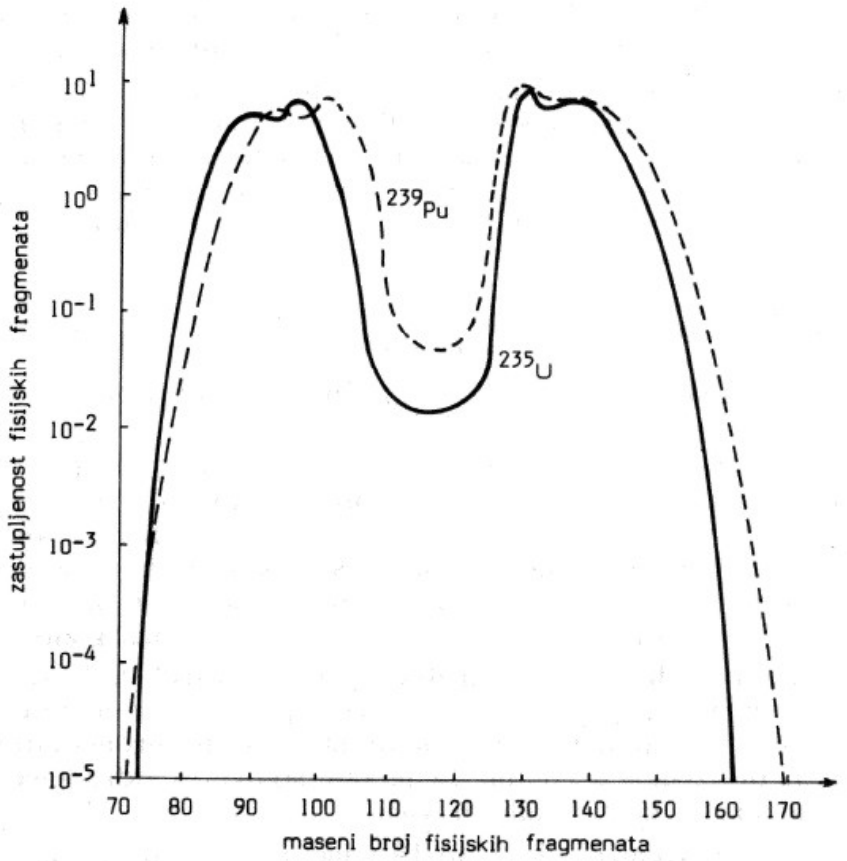
- Fisijom nastaju nova jezgra – fisijski fragmenti
- Postoji stotinjak načina na koji se teška jezgra može cijepati
- Novonastala jezgra su beta i gama radioaktivna jer imaju višak neutrona obzirom na broj protona Z
- Približno 180 MeV energije se oslobodi neposredno pri fisiji a oko 20 je posljedica radioaktivnog raspada fisijskih produkata
- Brzina osobađanja te zakašnjele energije ovisi o konstantama radioaktivnog raspada
- Radioaktivnost fisijskih produkata i pripadajuća toplina osnovni su sigurnosni problem u reaktoru
- Zaustavljanjem lančane reaktivnost ovaj izvor ne nestaje
- Neposredno nakon obustave ostatna toplina iznosi približno 6% nominalne snage na kojoj je reaktor radio
- Zbog velikog broja fisijskih produkata iznos ostatne topline uzimamo u obzir aproksimativnim relacijama

Fisijski produkti

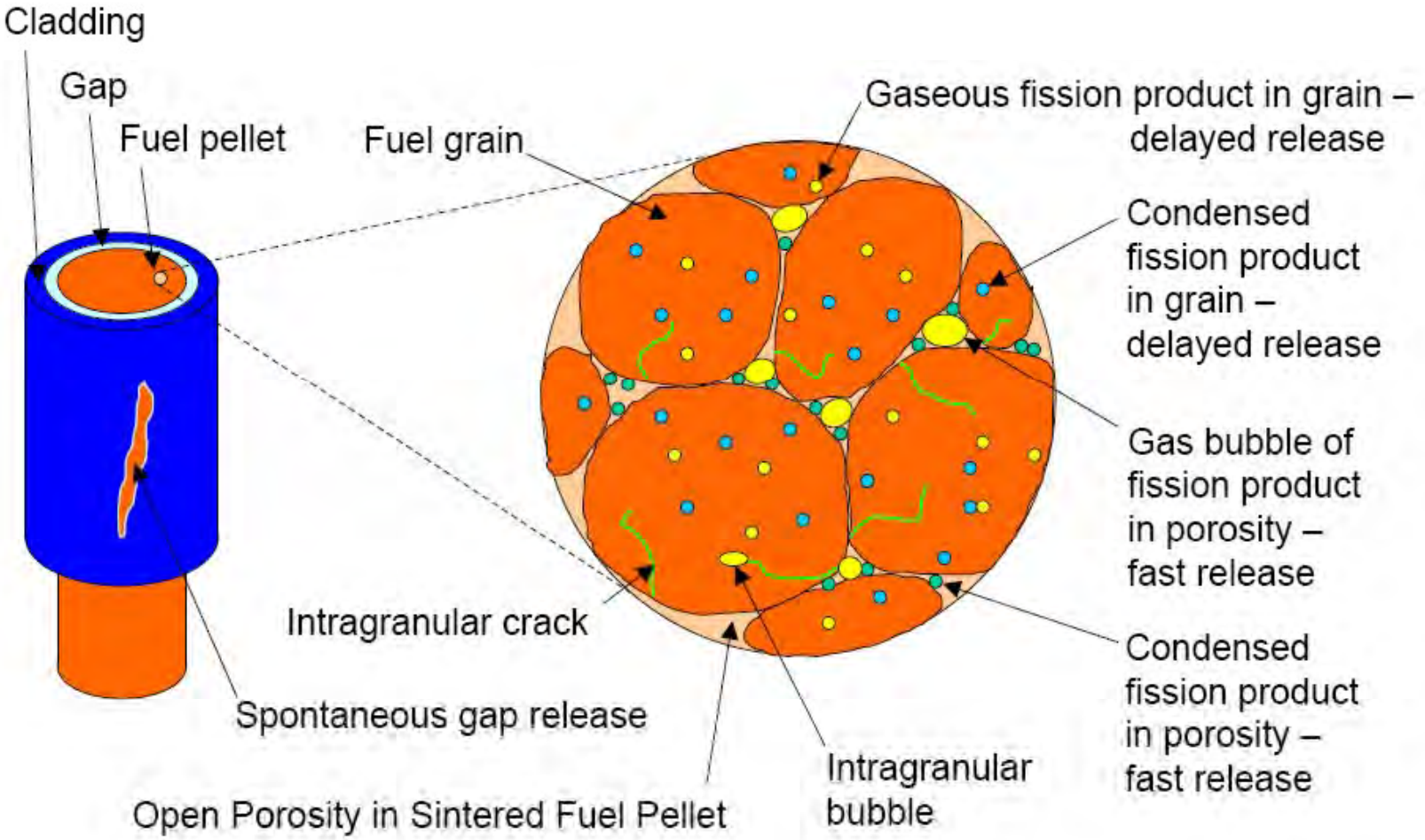
- plemeniti plinovi: Kr, Xe
- lako hlapljivi FP: I, Cs, Te ...
- srednje hlapljivi FP: Ba, La, Sr, Ru ...
- slabo hlapljivi FP: aktinidi, In, Cd ...

Ispuštanje FP u 2 faze:

1. “gap release”: ispuštanje plinovitih FP iz zazora nakon pucanja košuljice
2. nakon topljenja goriva ispuštaju se preostali plinoviti FP i lako hlapljivi FP



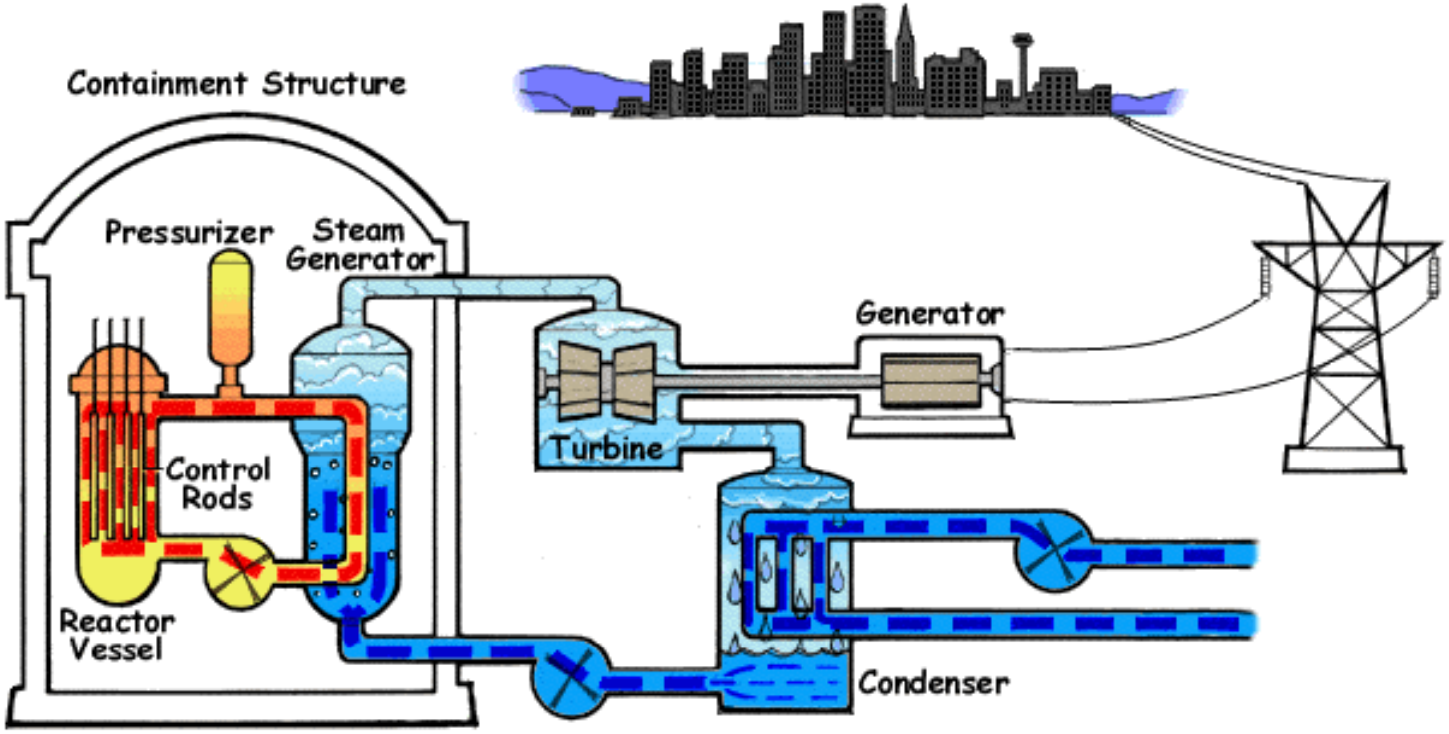
Fisijski produkti



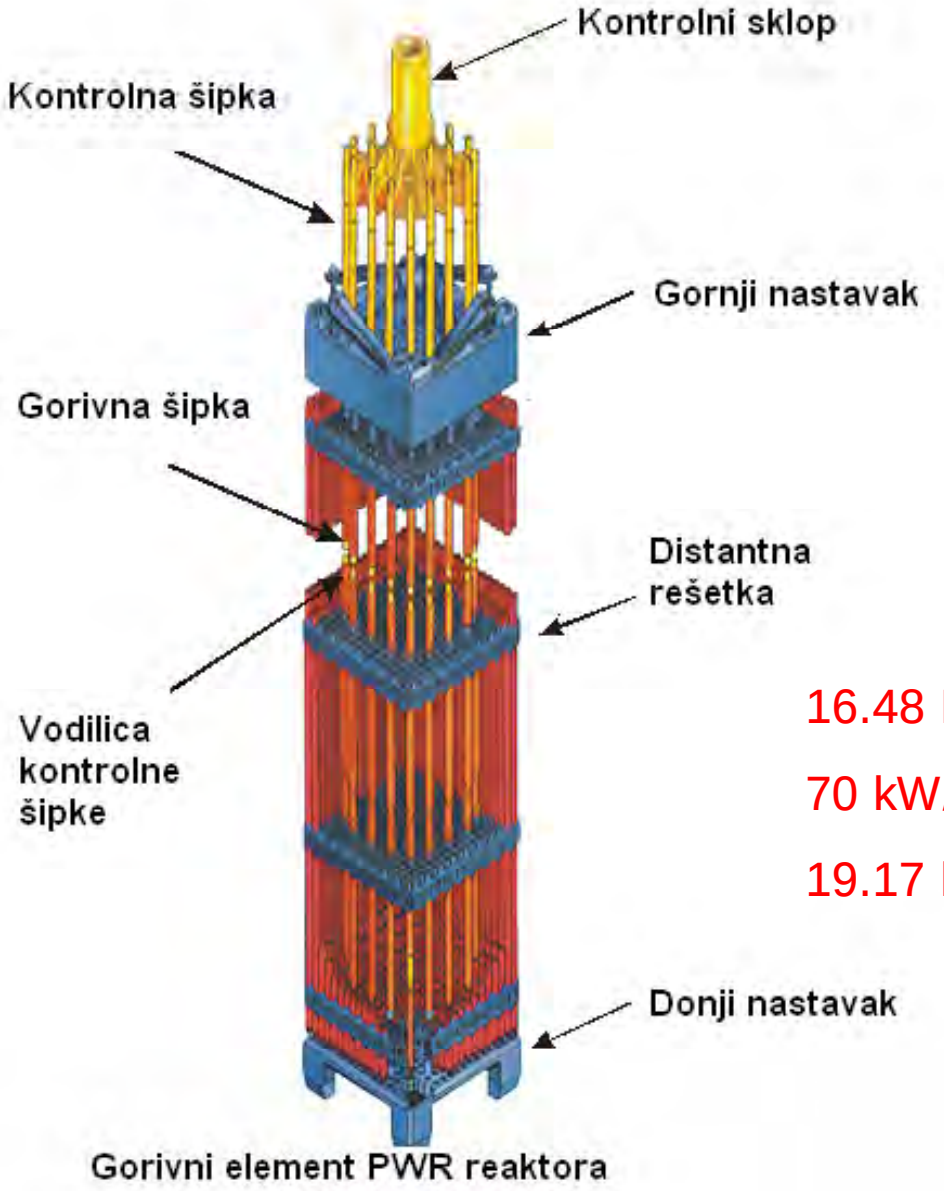
NE PWR – princip rada

Tipični parametri PWR-a:

- **primarni tlak 15 do 16 MPa** — **sekundarni tlak 6 do 8 MPa**
- **prosječna primarna temp. 570-590 K** — **temperatura pojne vode 490 K**
- **porast temp. u reaktoru 40 do 50 K**
- **protok po rashl. krugu 6 m^3/s (oko 4500 kg/s)** — **protok pare po parogeneratoru 520 kg/s**



Gorivni element i gorivna šipka

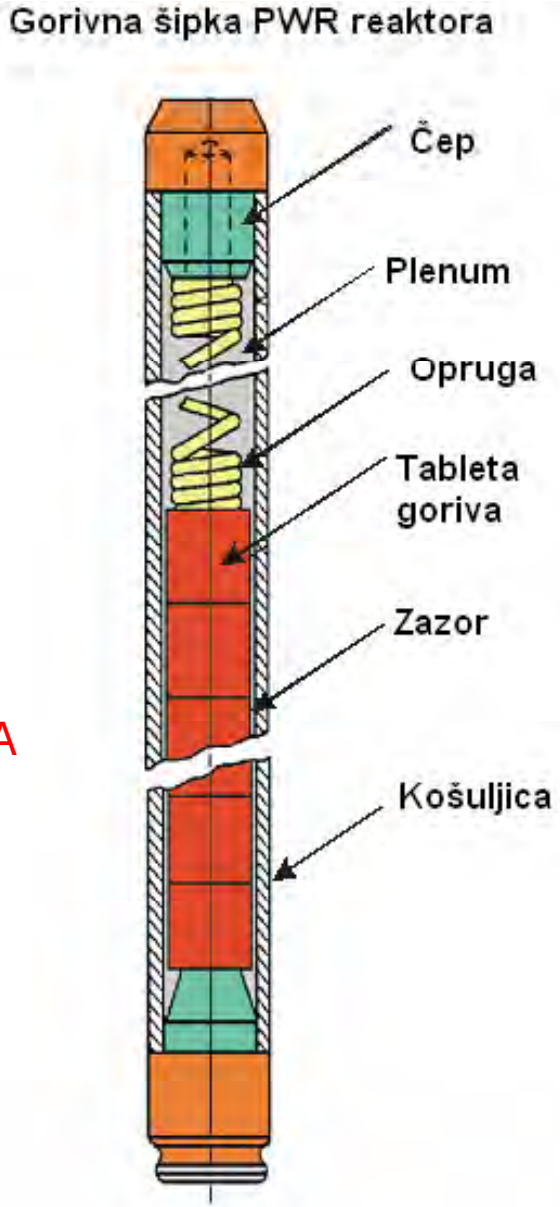


Gorivni element PWR reaktora

16.48 MW/FA

70 kW/šipka

19.17 kW/m



Sigurnost nuklearnih elektrana

- Zanemarive emisije u normalnom pogonu
- Konzervativan projekt s visokim stupnjem sigurnosti
- Visoki zahtjevi na kvalitetu materijala i ugradnju
- Da bi se postigao siguran pogon potrebno je:
  - *spriječiti nagle poraste snage*
  - *osigurati odvođenje ostatne topline*
  - *spriječiti ispuštanje radioaktivnog materijala*
  - *pospremiti na siguran način istrošeno gorivo*

Principi sigurnosnih mjera u nuklearnim elektranama

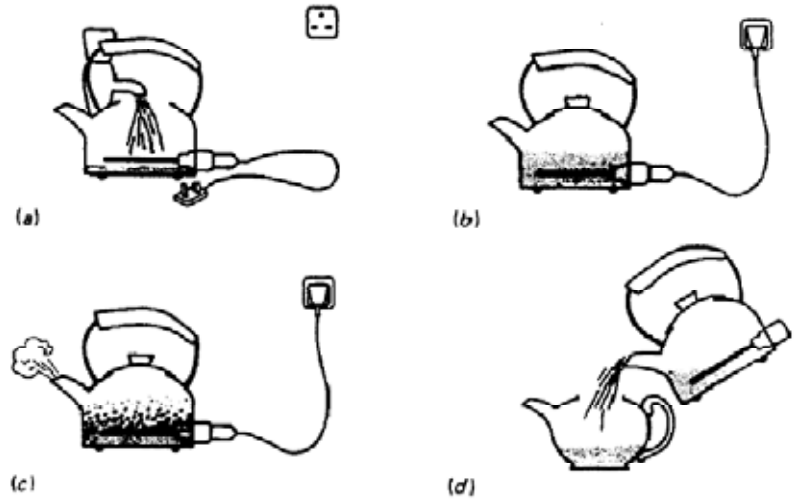
- **Nuklearna eksplozija reaktora je onemogućena projektom**
- **U svojoj jezgri nuklearni reaktor sadrži veliku količinu radioaktivnih tvari, pretežno fisijskih proizvoda.**
- **Sigurnost se u osnovi odnosi na onemogućenje širenja radioaktivnih materijala unutar postrojenja i u okoliš**
- **Do akcidentnog ispuštanja uglavnom dolazi samo ako dođe do pregrijanja goriva**
- **Sigurnost nuklearne elektrane se postiže nizom mjera u fazi projektiranja, gradnje i tijekom pogona.**

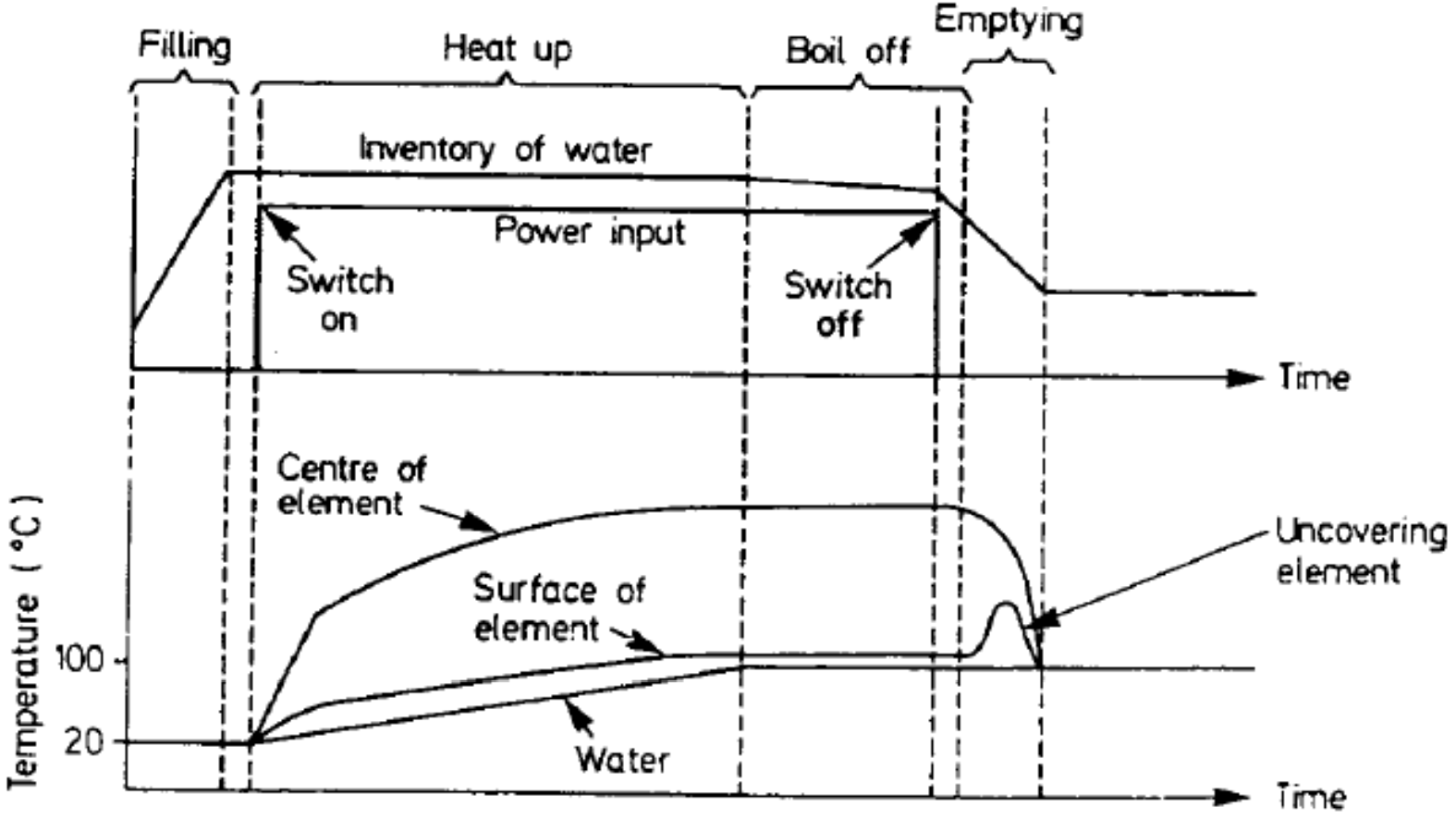
Da li je nuklearna elektrana tempirana nuklearna bomba?

Nuklearna eksplozija nije moguća za obogaćenje i sastav jezgre u reaktoru

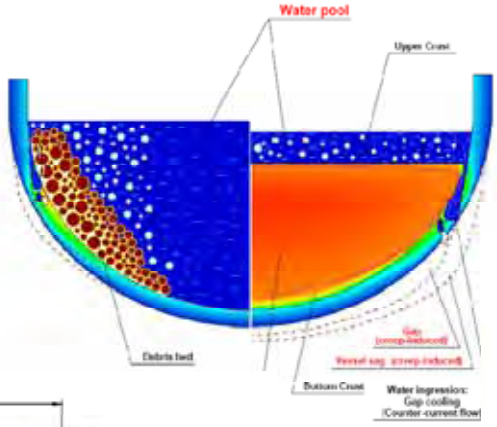
Ali je potrebno spriječiti i ograničiti promptne poraste snage

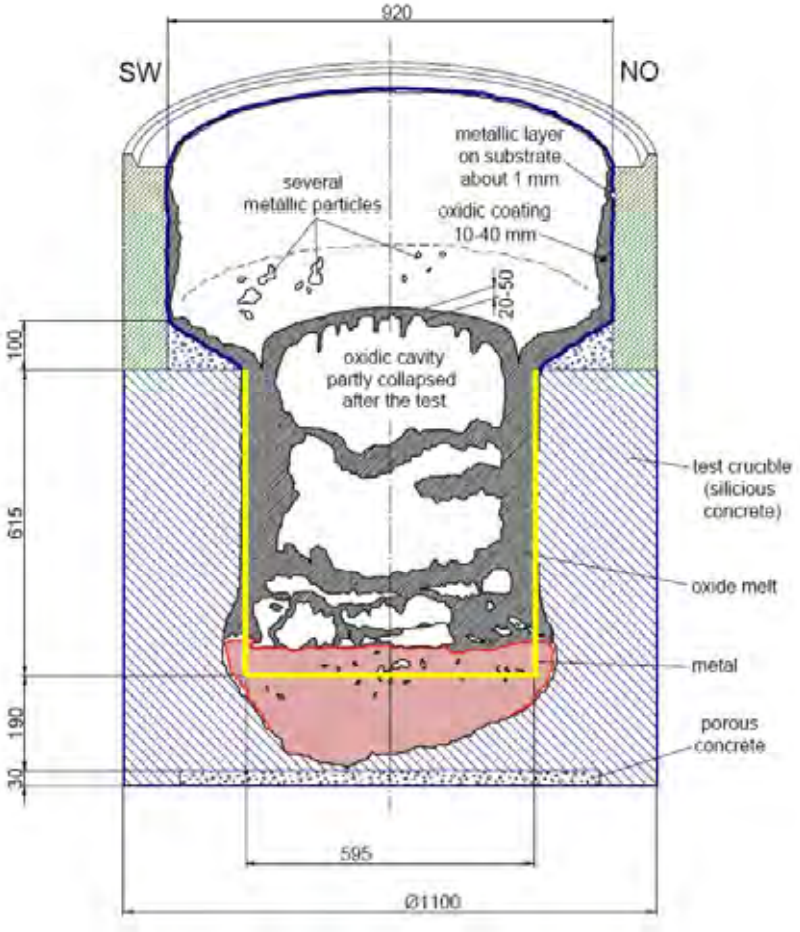
Odvođenje topline

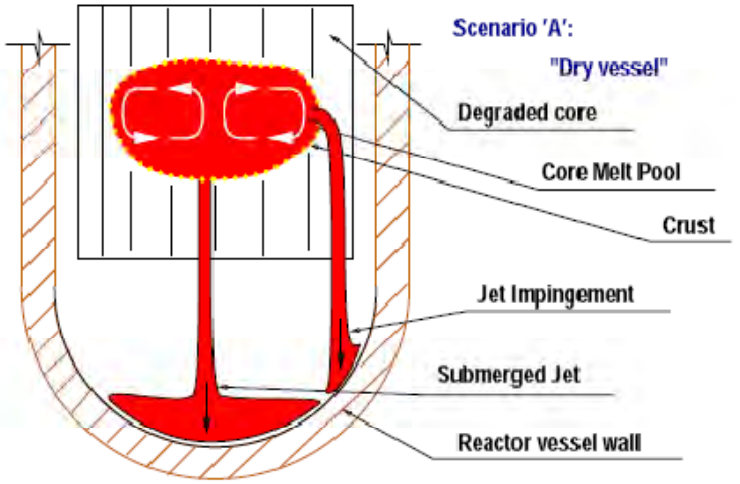


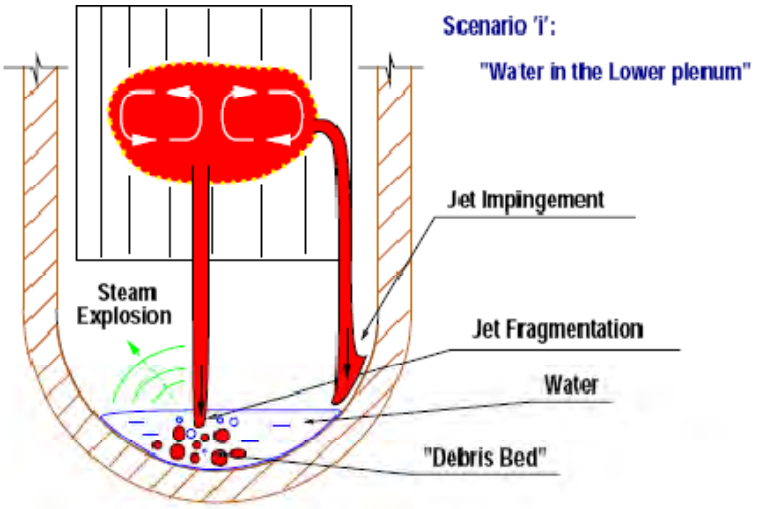


Kineski sindrom – da li je moguć?





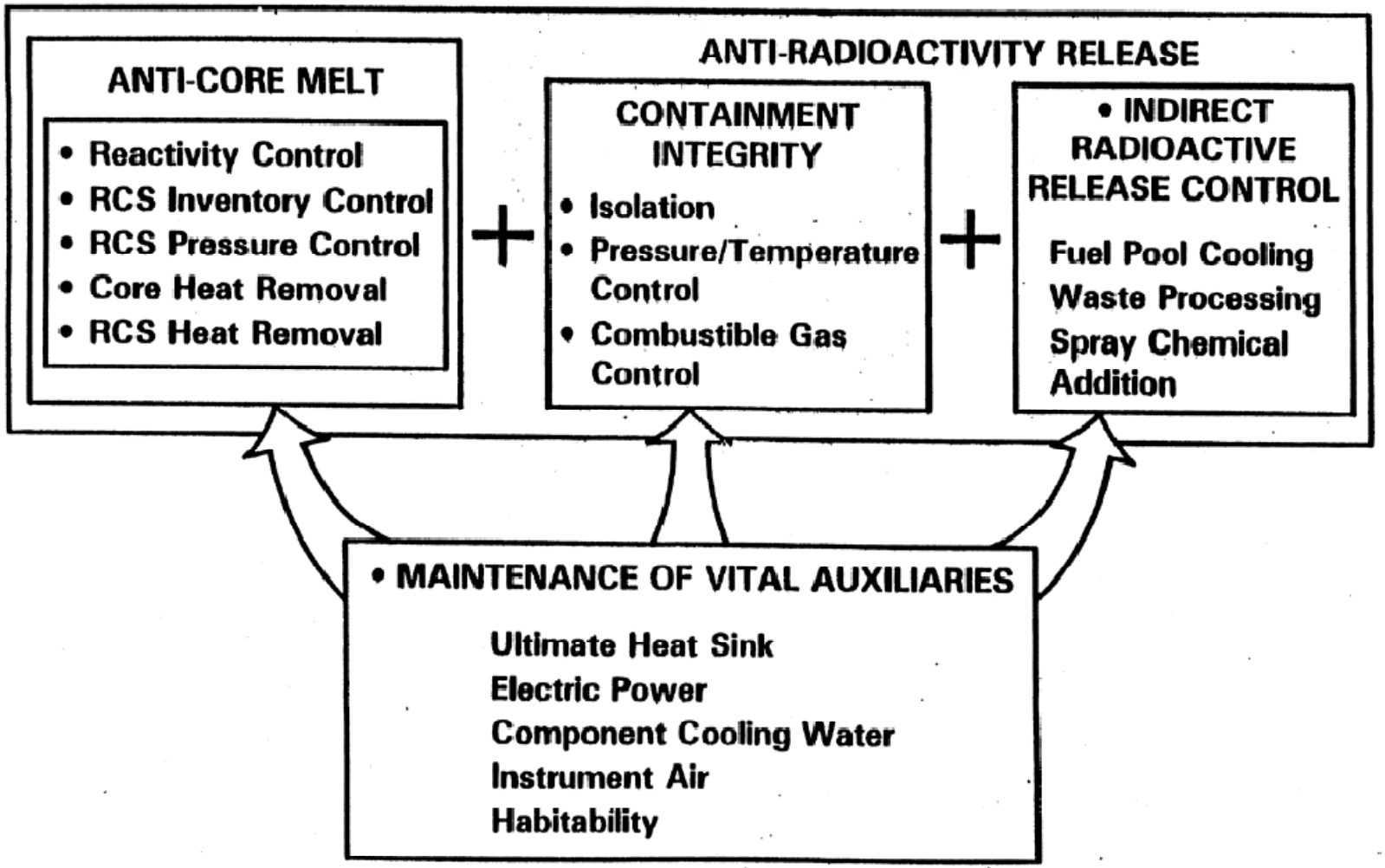




Porast temperature jezgre obustavljen reaktor bez hlađenja

- Ostatna toplina 30 MW.
- 100,000 kg materijala u jezgri.
- Pretpostavljena srednja specifična toplina materijala jezgre 600 J/kg-C.
- Porast temperature C/s.
- Nakon 30 min srednja temperatura jezgre bi porasla 900 C.

Kritične sigurnosne funkcije



Obrana po dubini

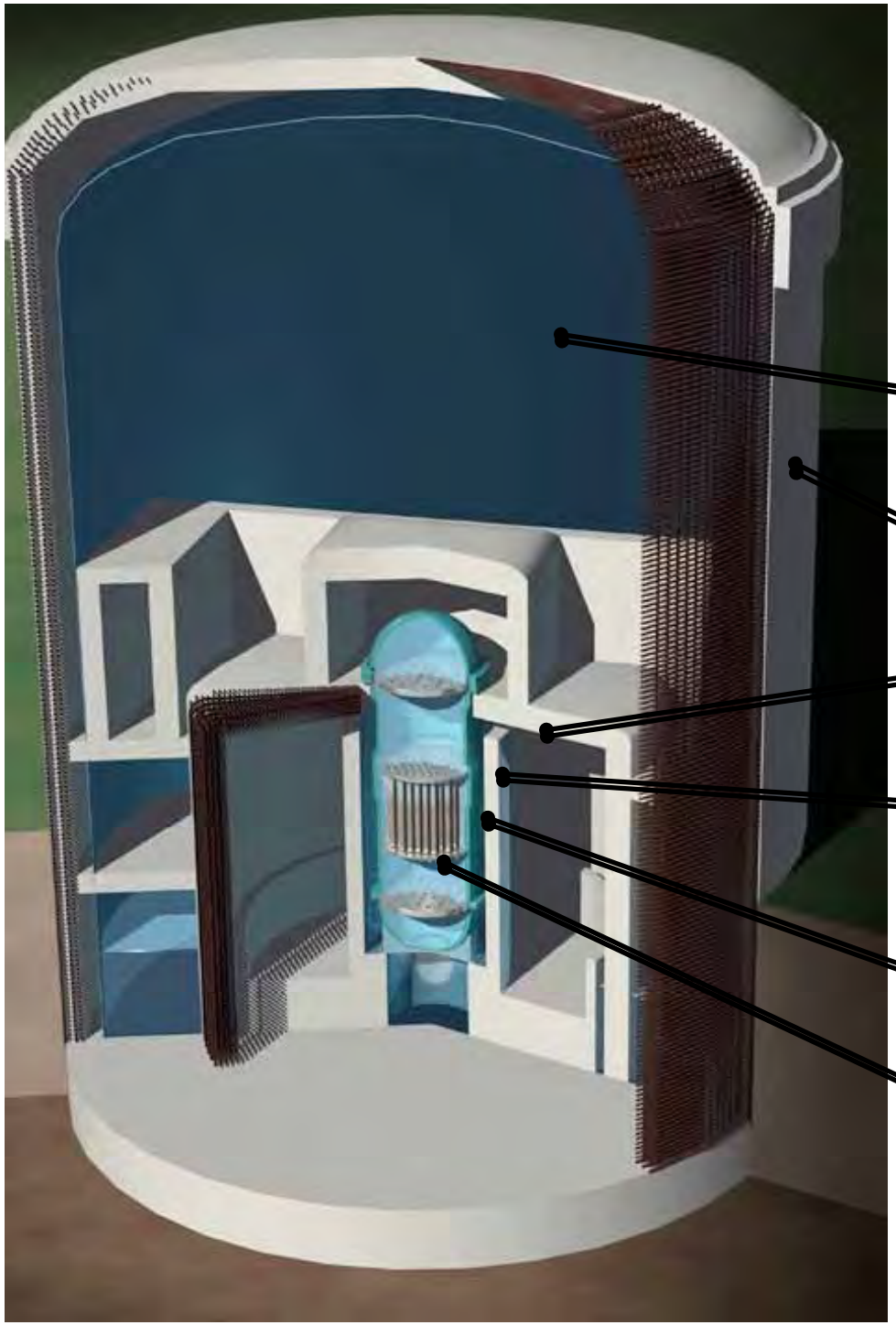
- **Osnova filozofije projektiranja nuklearne elektrane sa stajališta sigurnosti je tzv. obrana po dubini.**
- **Obrana po dubini pretpostavlja postojanje višestrukih barijera za širenje radioaktivnosti i sigurnosnih sustava koji osiguravaju njihovu nepropusnost**
- **Barijere u smislu zaštite okoliša djeluju serijski, jedna nakon druge.**
- **Izgubljenu funkciju jednog sustava važnog za sigurnost automatski preuzima drugi.**
- **Bitni sustavi su u najmanju ruku udvojeni**
- **Sustavi mogu biti aktivni ili pasivni (kako dobivaju energiju potrebnu za izvršavanje sigurnosne funkcije)**
- **Barijere možemo razmatrati kao stvarne fizičke barijere ugrađene u nuklearnu elektranu i kao fizičke i administrativne mjere koje se poduzimaju u nuklearnoj elektrani za zaštitu tih barijera.**

Obrana po dubini

- **Fizičke barijere su:**
  - **matrica nuklearnog goriva**
  - **obloga gorivnog elementa**
  - **primarni rashladni krug**
  - **zaštitna posuda (kontejnment)**

- **Tehnički sustavi koji osiguravanju funkciju fizičkih barijera:**
  - **sustav za zaštitno hlađenje jezgre reaktora (štiti gorivne elemente od pregrijanja)**
  - **sustav za ograničavanje porasta tlaka u kontejnmentu (štiti zaštitnu posudu od previsokog tlaka i temperature)**

Višeslojna zaštita



Kontejnmentska posuda
4 cm čelika

Kontejnmentska zgrada
1 m prenapregnutog betona

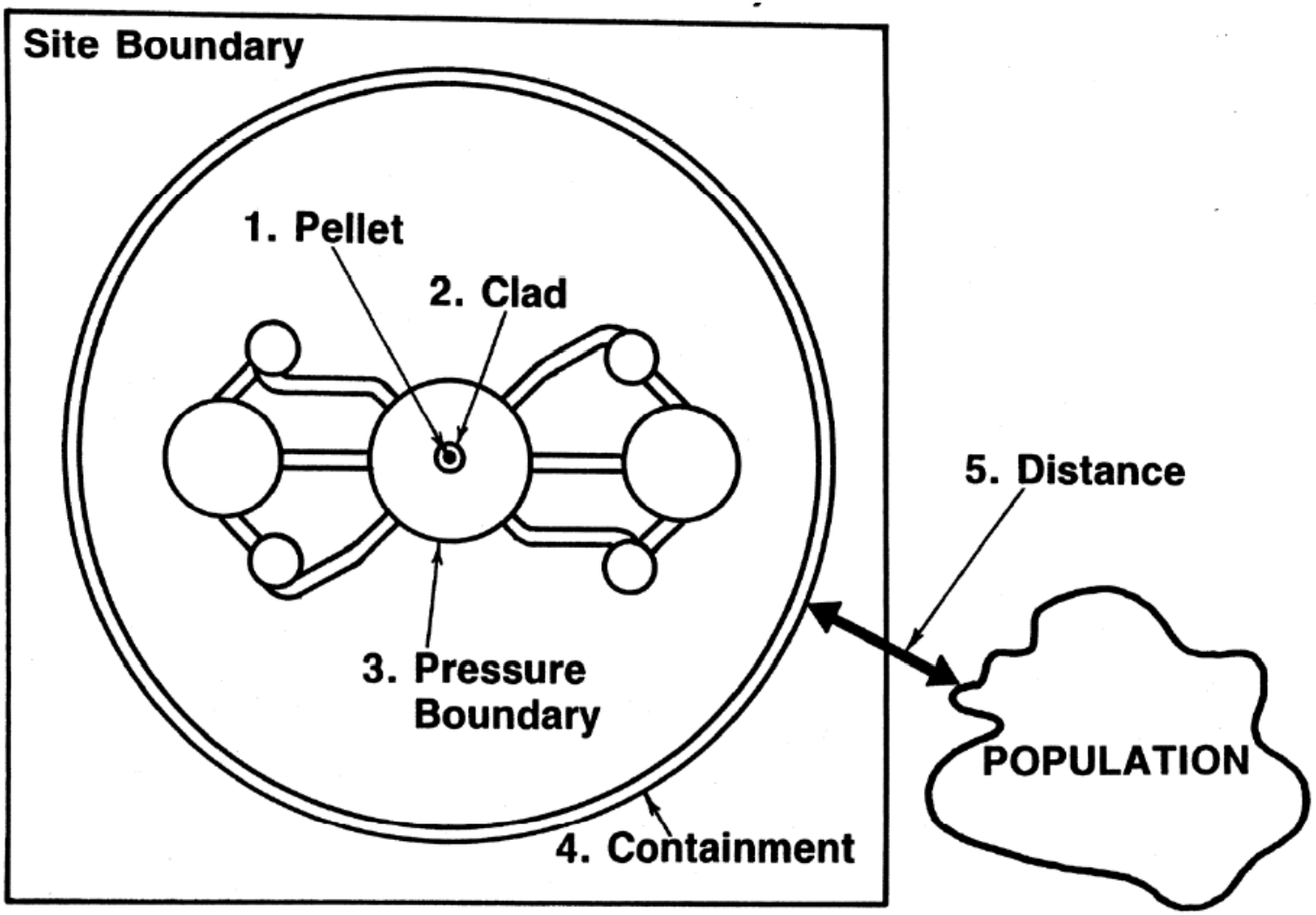
Unutrašnja betonska struktura
1.5 m prenapregnutog betona

Biološki štit
1,2 m teškog betona +
4 cm čelika

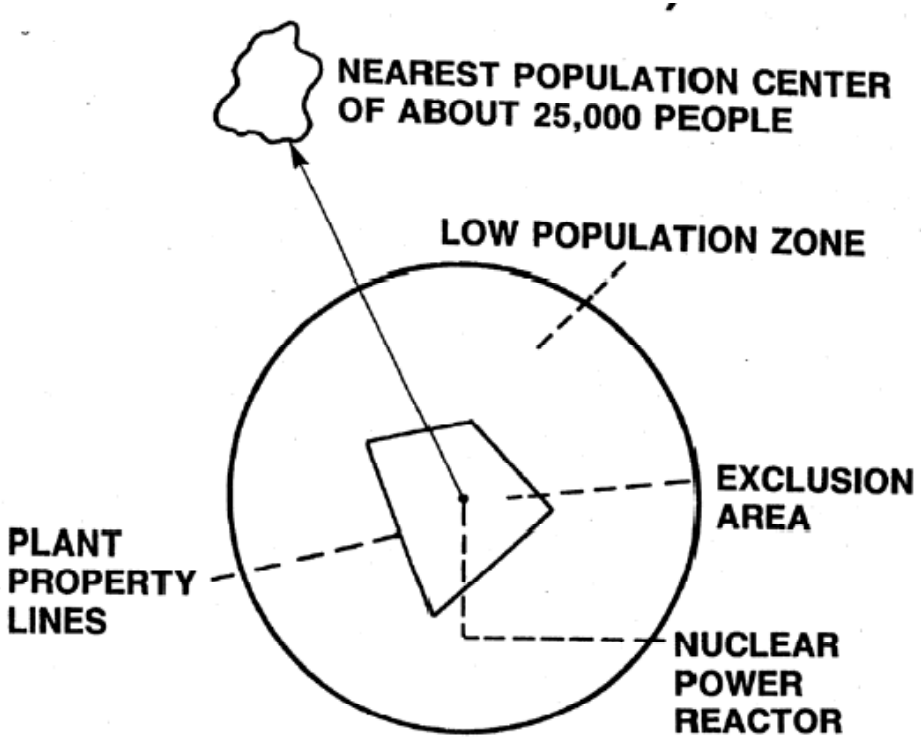
Reaktorska posuda
20 cm čelika

Matrica goriva + košuljica

Prostorni aspekt obrane po dubini

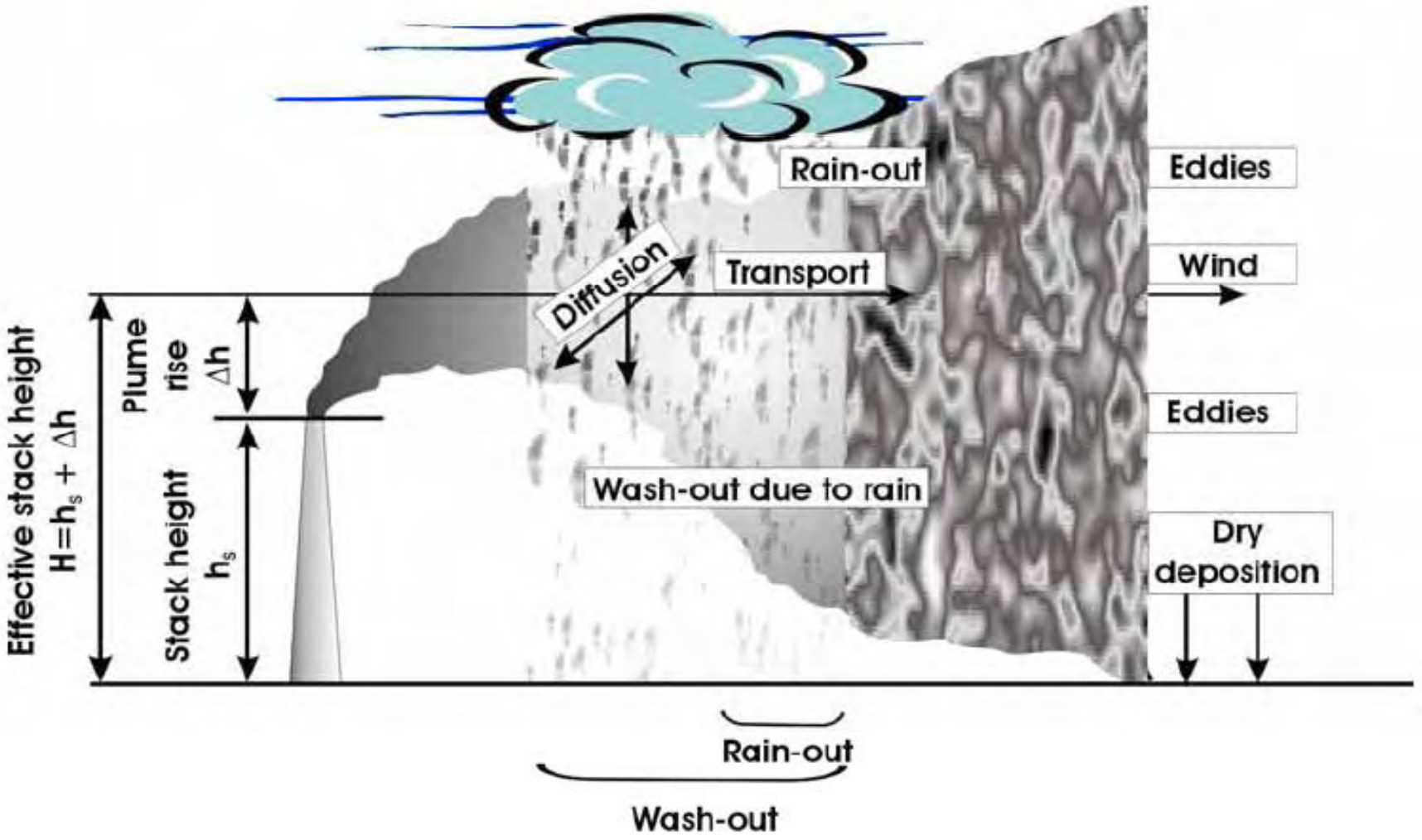


Lociranje elektrane

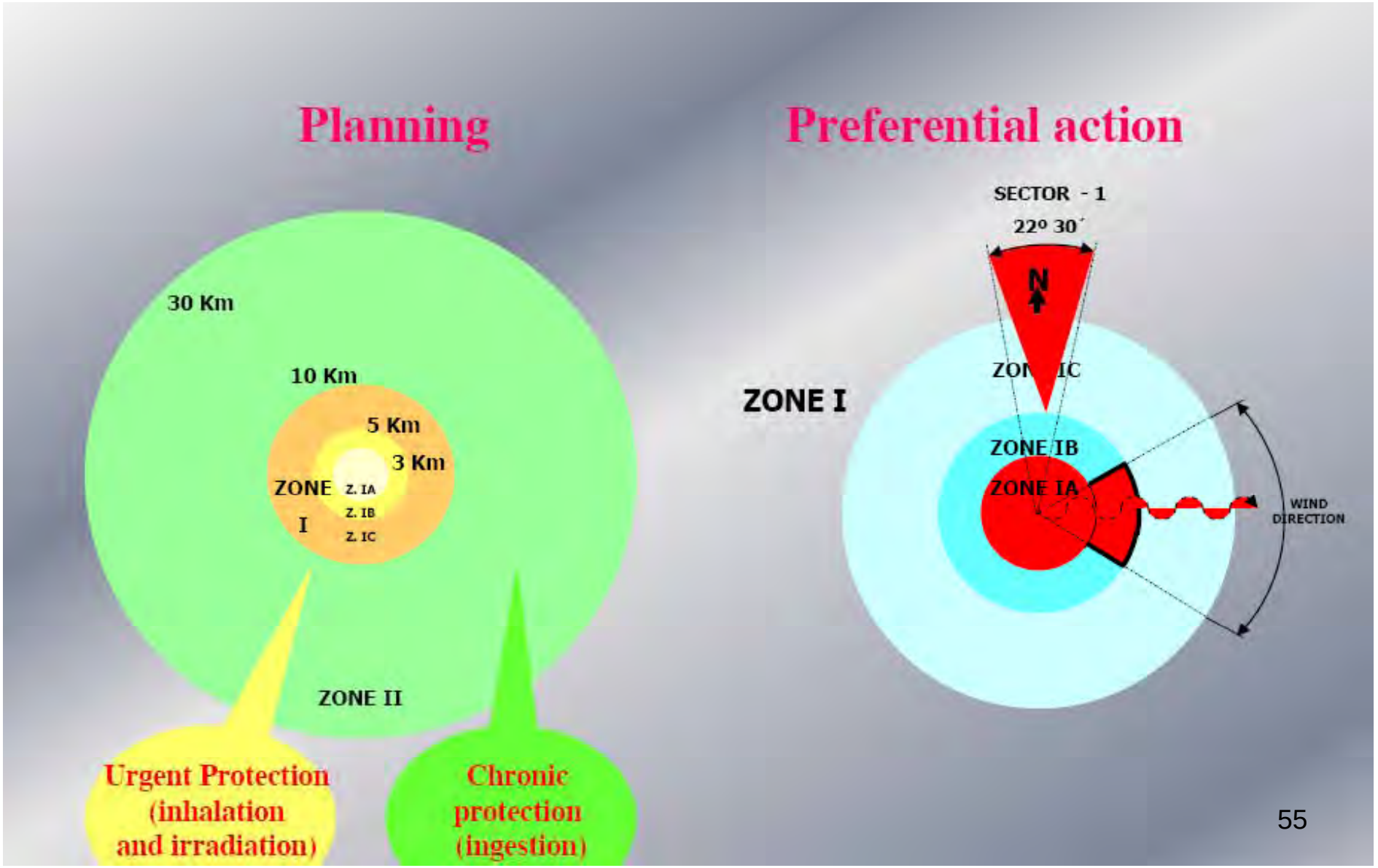


- At Boundary of Exclusion Area, No Member of Public May Exceed 25 rem Whole-Body Dose for Design Basis Accident
- Timely Evacuation of Low Population Zone Must be Planned
- Population Center Must Be at Least 1-1/3 Times Farther Away than LPZ Boundary

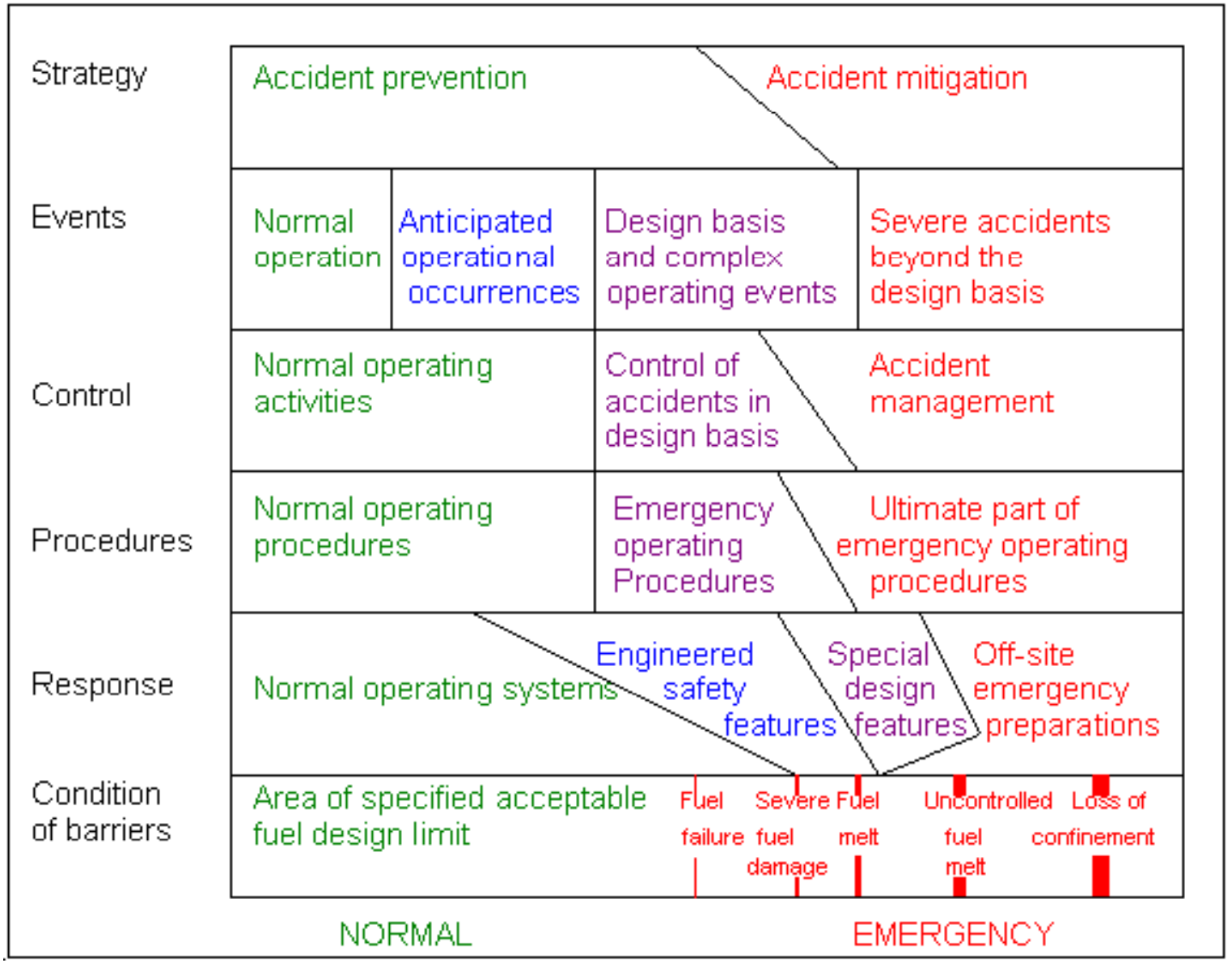
Ponašanje efluenata oslobođenih u atmosferu



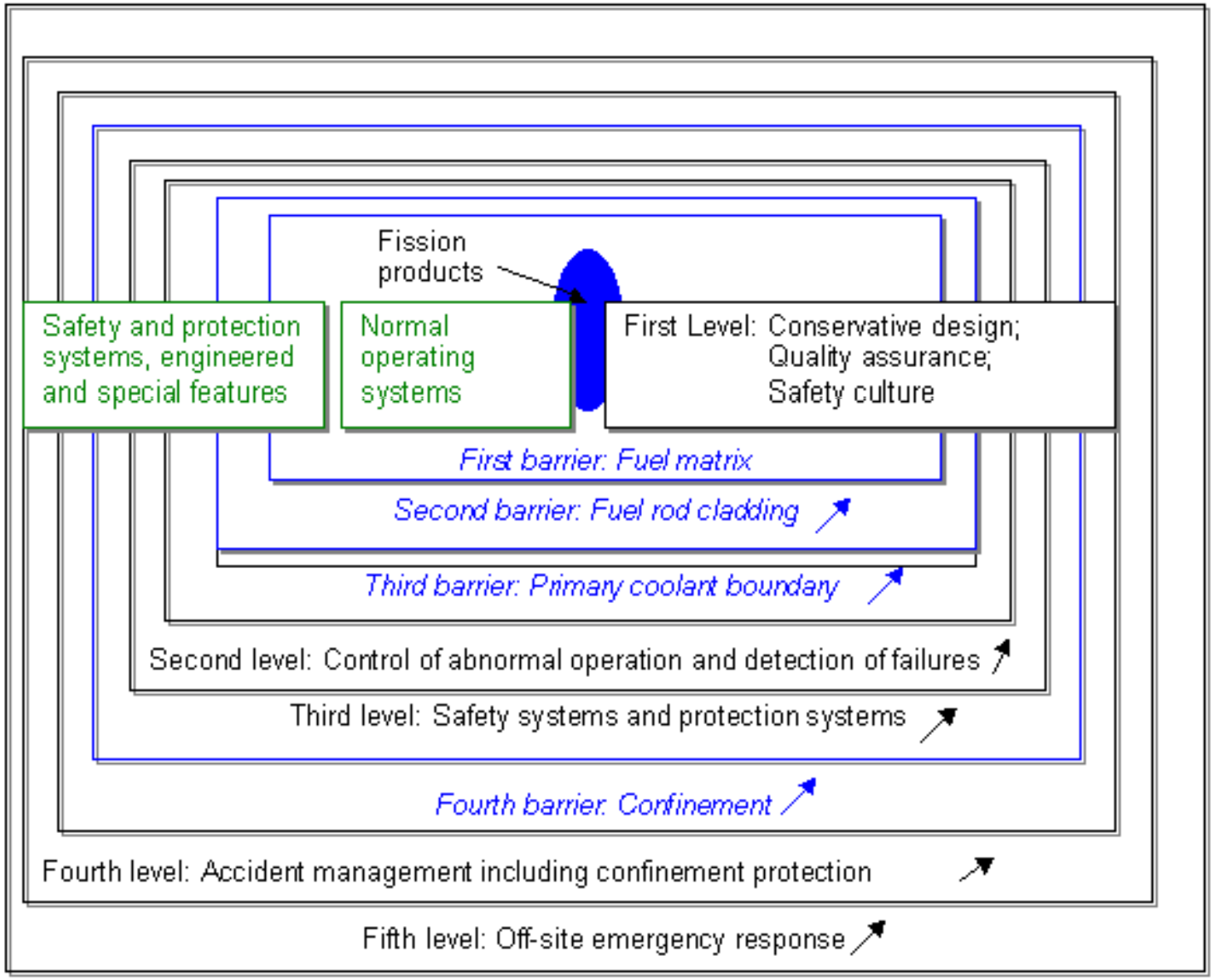
Planovi u slučaju nuklearne nesreće



Ideja obrane po dubini



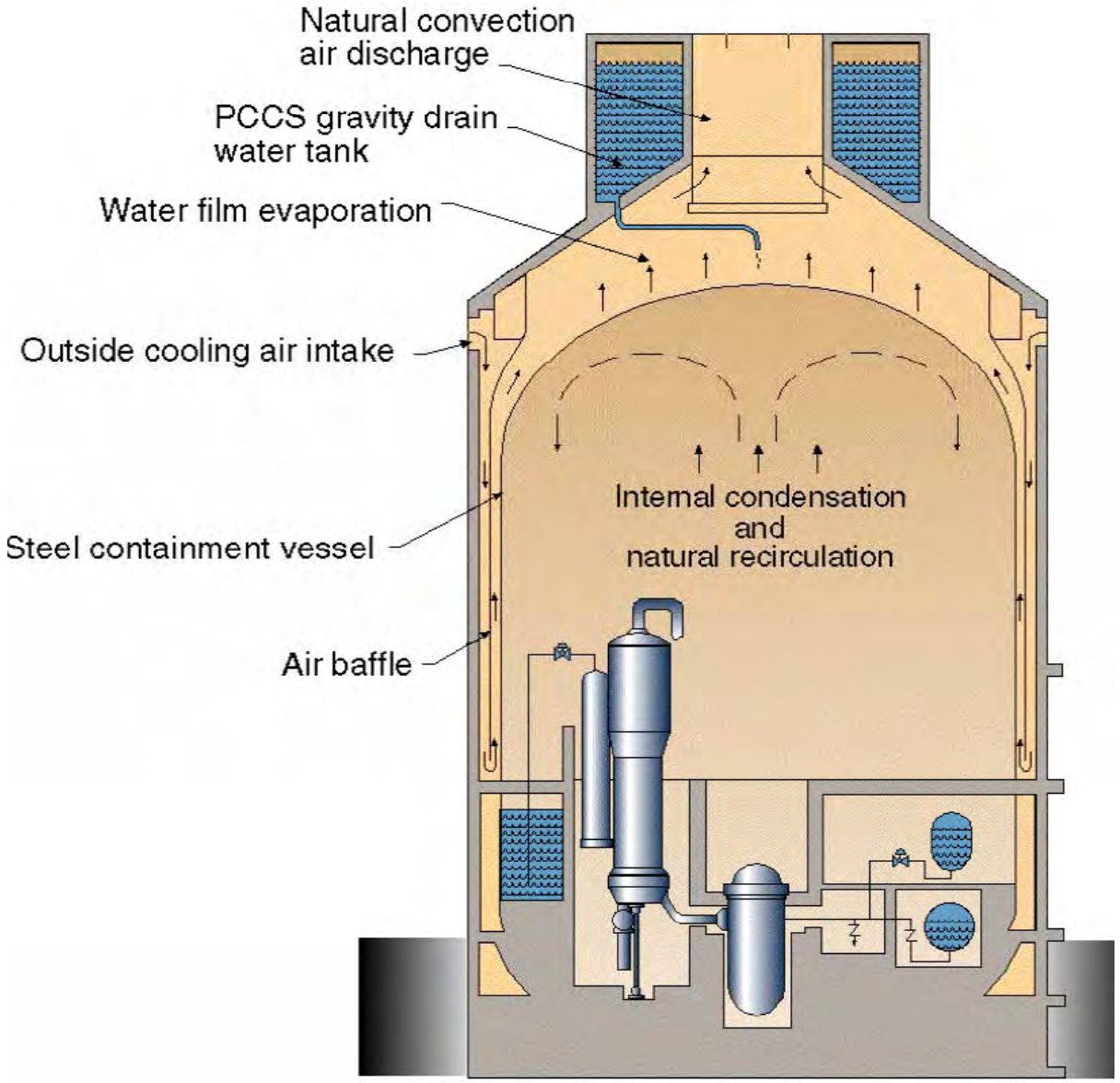
Relacija između fizičkih barijera i nivoa obrane po dubini



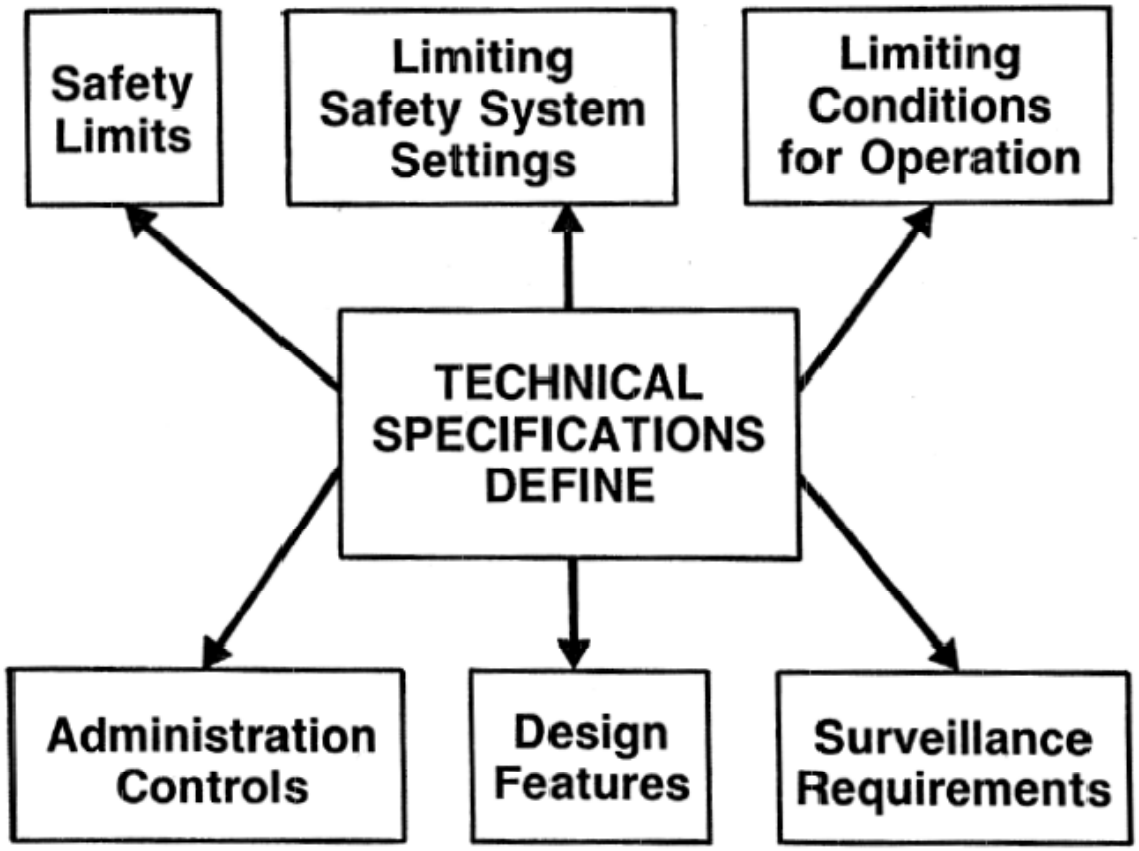
Principi projektiranja sigurnosnih sustava

- Jednostruki otkaz
- Redundantnost
- Diverzitet
- Neovisnost sustava
- Fizička separacija
- Sigurni smjer greške
- Provjera stanja sustava
- Aktivna i pasivna sigurnost

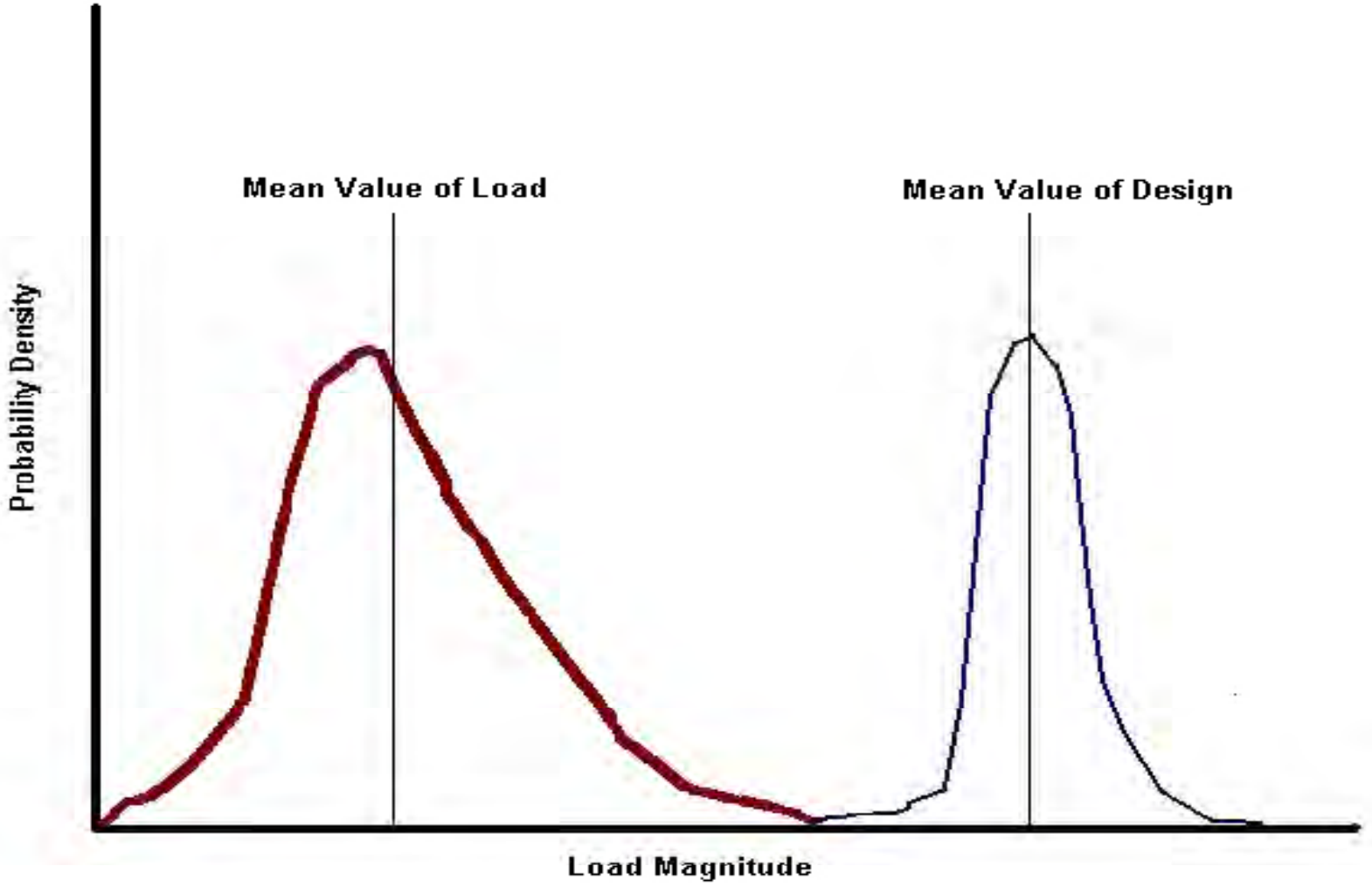
Pasivni sigurnosni sustavi
Primjer AP1000



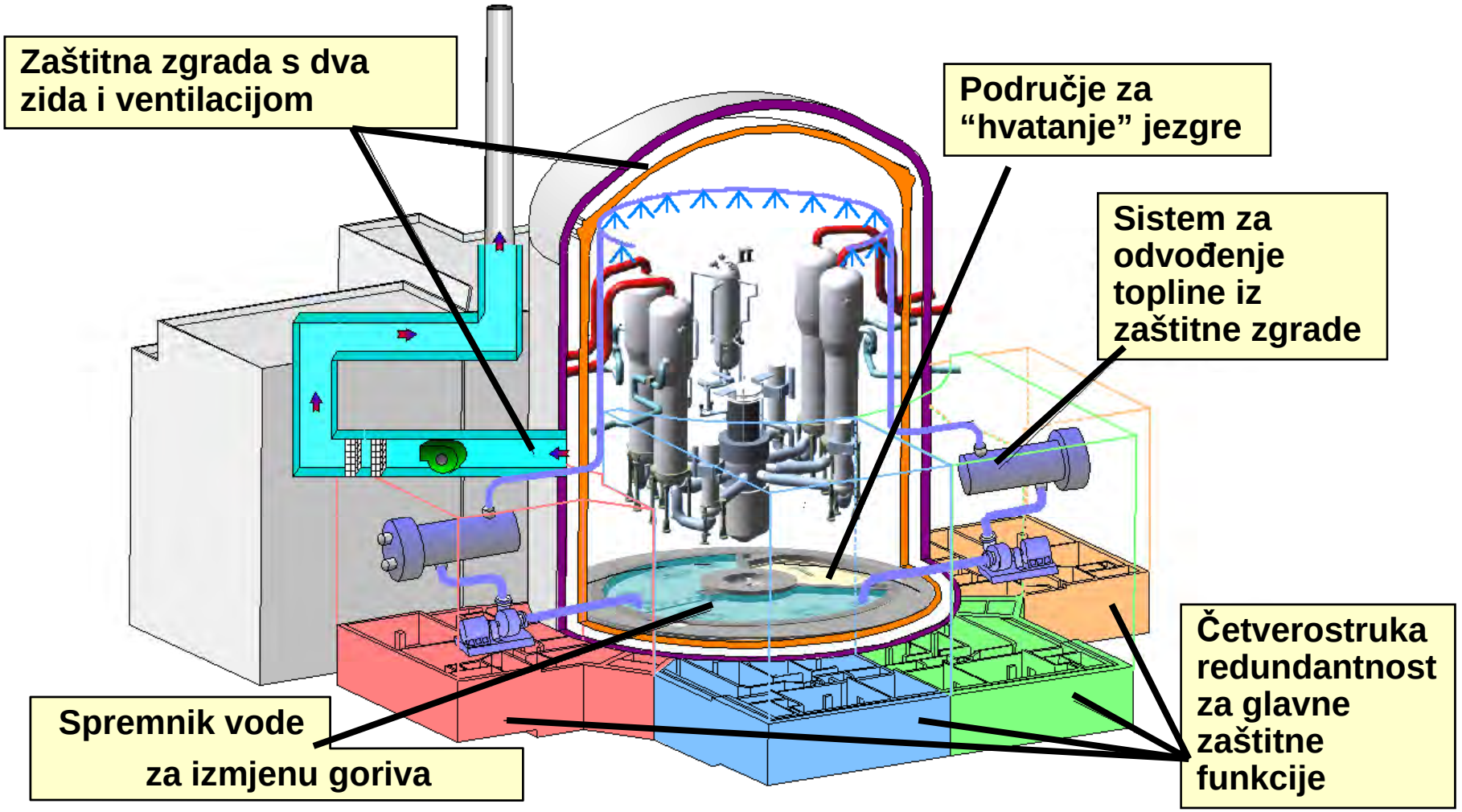
Sigurnosni limiti i postavne vrijednosti



Projektne margine



Evolutivni PWR – EPR



Analize sigurnosti elektrane

- Cilj je demonstrirati da NE može biti u pogonu bez nepotrebnog rizika za zdravlje ljudi i sigurnost
- Aplikacija za pogonsku dozvolu uključuje dokumentirano stanje sigurnosti elektrane - sigurnosni izvještaj elektrane (Final Safety Analysis Report - FSAR)
- Sigurnosni izvještaj mora sadržavati analizu projekta i pogonskih svojstava elektrane da se pokaže postojanje sigurnosnih margina za sve relevantne sigurnosne limite za vrijeme normalnog pogona, tranzijenata i projektnih akcidenata za cijelo vrijeme života elektrane

Događaji od značaja za sigurnost

- Svrha evaluiranja širokog spektra događaja u sigurnosnim analizama je da se ocjene sva pogonska stanja elektrane i da se demonstrira suglasnost s regulatornim zahtjevima i uvjetima navedenim u pogonskoj dozovoli
- Da se osigura sustavan pristup koristi se kategorizacija događaja po frekvenciji pojavljivanja, težini posljedica i prirodi poremećaja

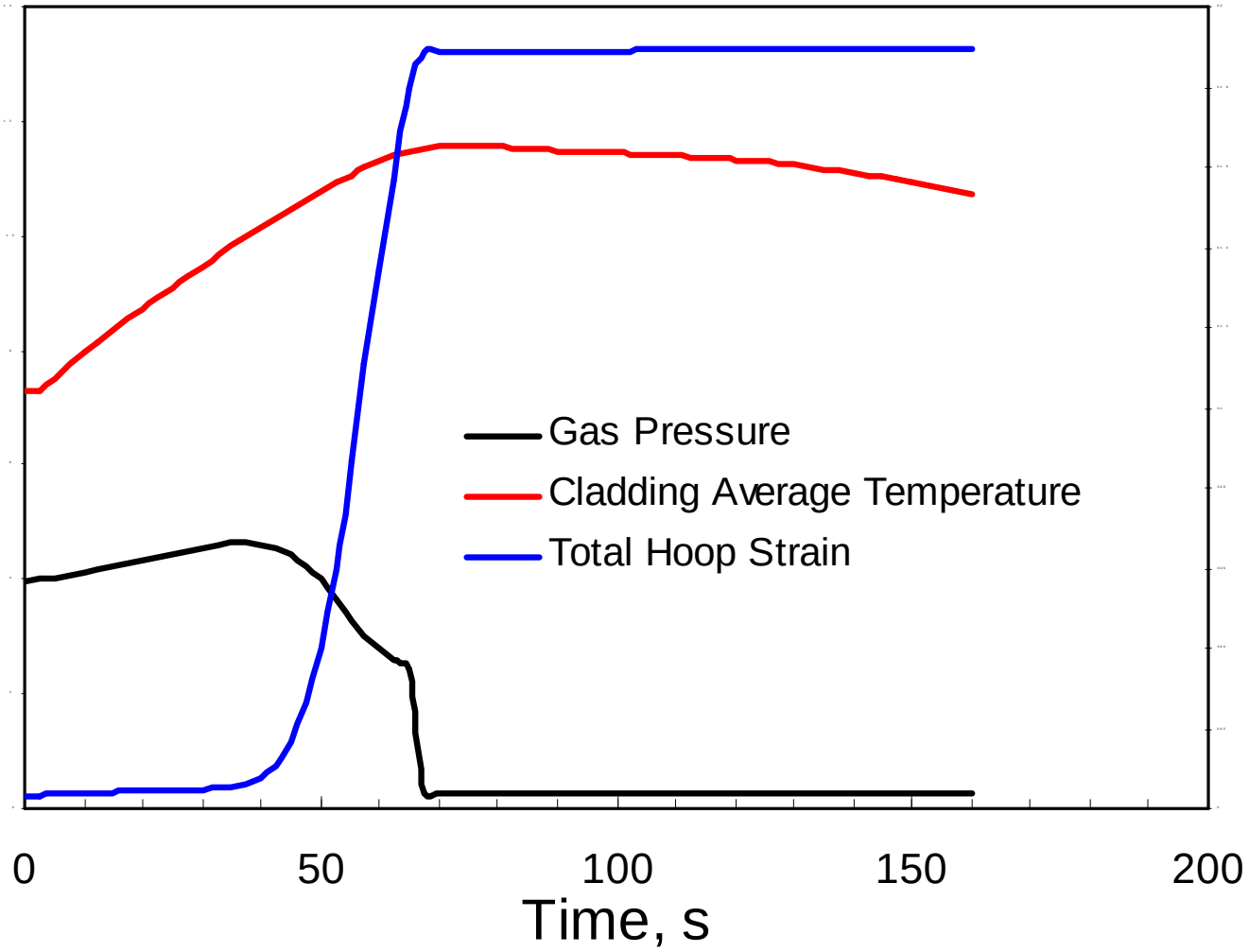
Unutarnji i vanjski inicirajući događaji

1. **Normalni pogon**
2. **Očekivani pogonski događaji**
   (frekvencija veća od 1e-2/god)
3. **Projektne nesreće (DBA)**
   (frekvencija 1e-2 do 1e-5 /god)
4. **Izvan projektne (BDBA) i teške nesreće**
   (frekvencija 1e-4 do 1e-5 /god CDF
   frekvencija 1e-5 do 1e-6 /gof LRF)

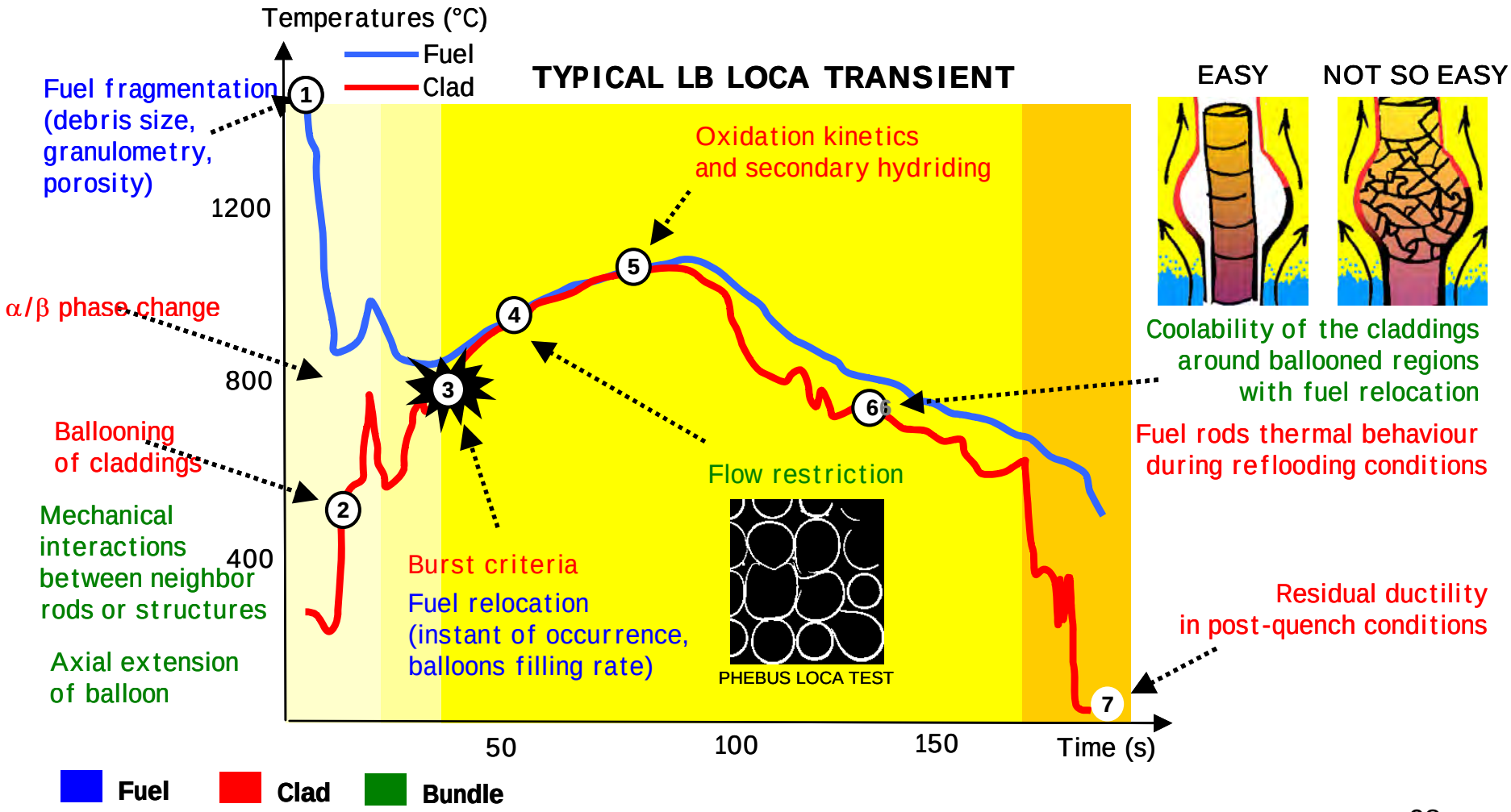
Funkcionalna klasifikacija događaja

1. Increase In Heat Removal By The Secondary System
2. Decrease In Heat Removal By The Secondary System
3. Decrease In Reactor Coolant System Flow Rate
4. Reactivity And Power Distribution Anomalies
5. Increase In Reactor Coolant Inventory
6. Decrease In Reactor Coolant Inventory
7. Radioactive Release From A Subsystem Or
8. Component
9. Anticipated Transients Without Scram

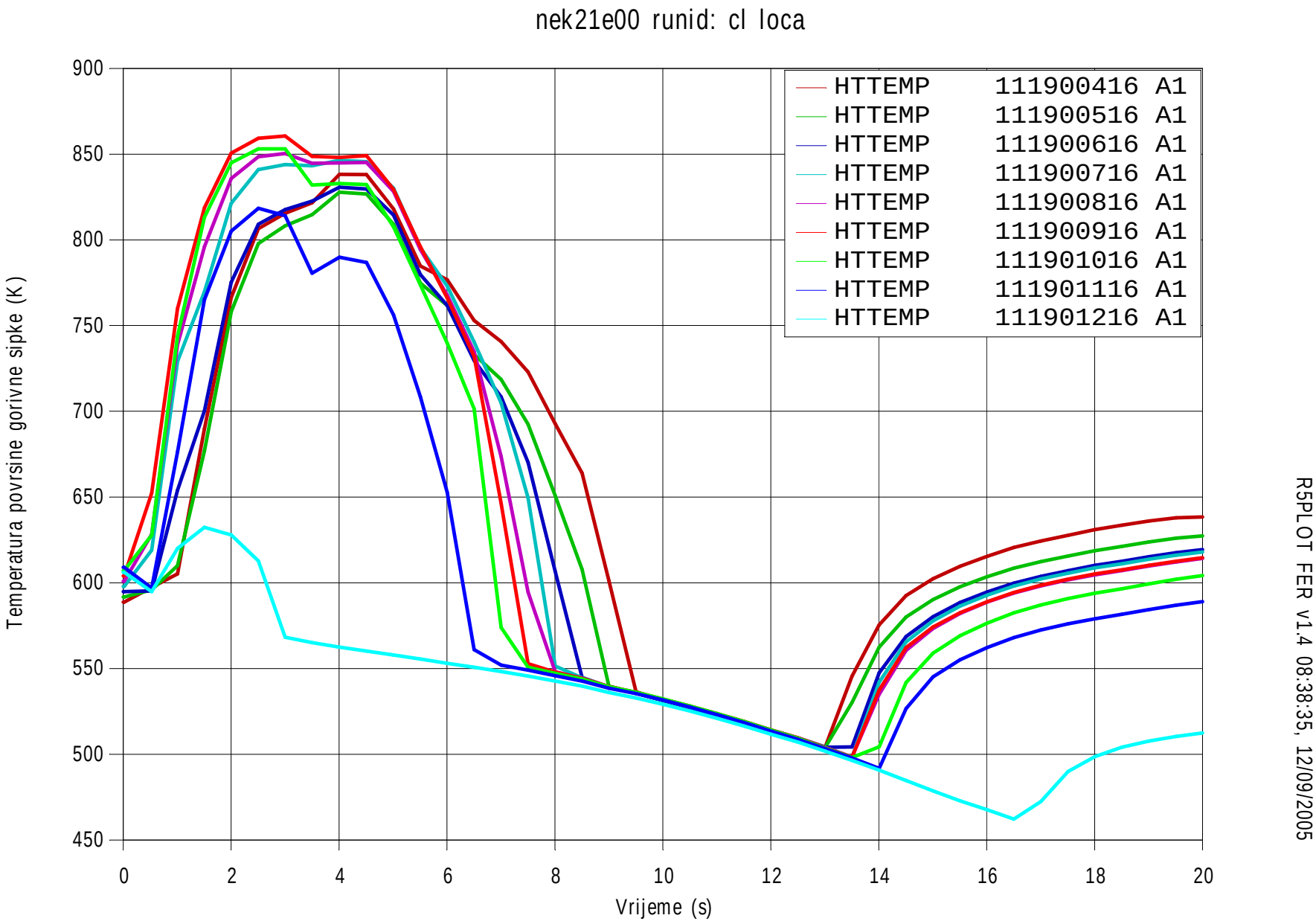
Tipični LOCA odziv



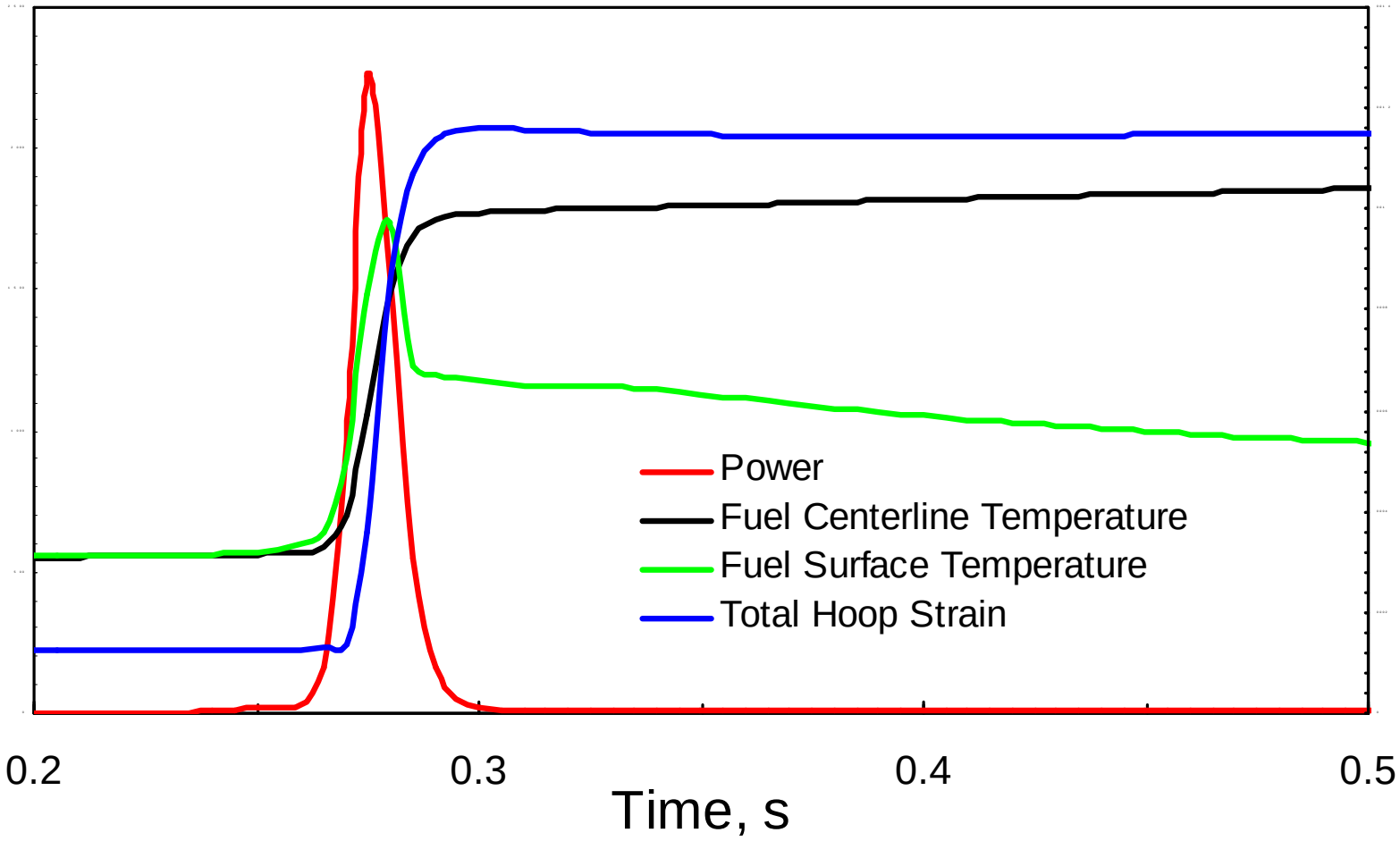
Tipični LOCA odziv



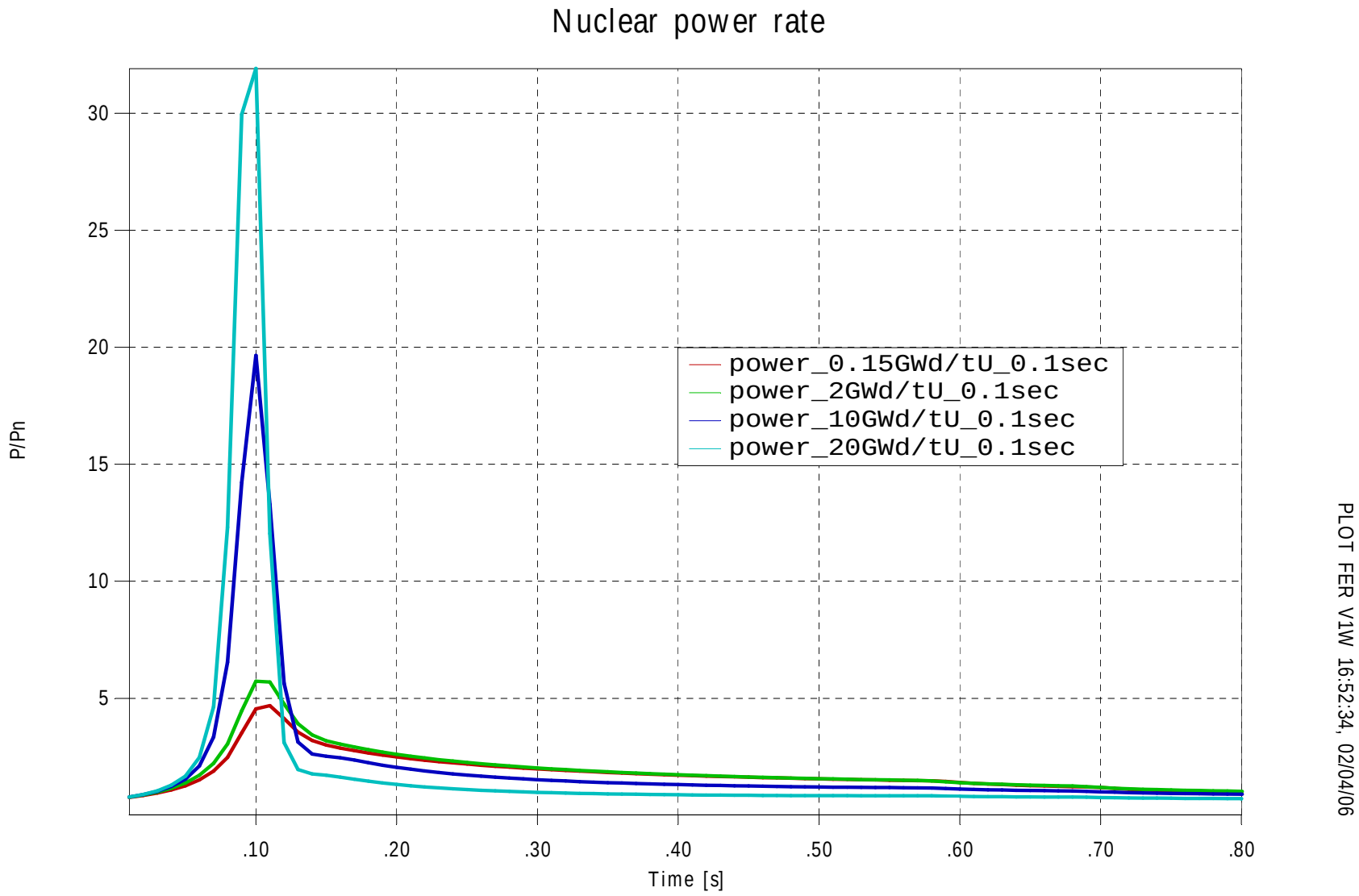
LOCA temperatura košuljice



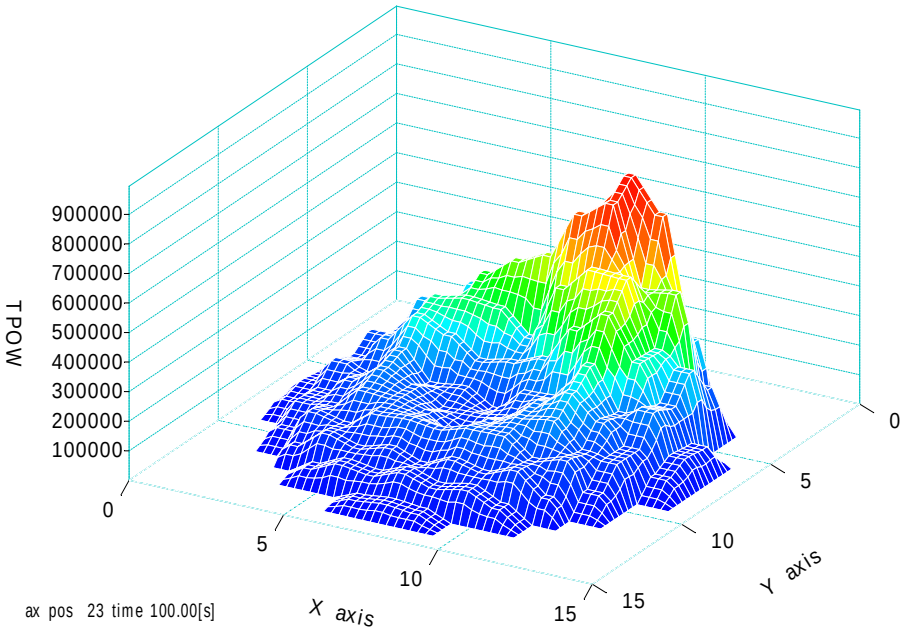
Tipični RIA odziv

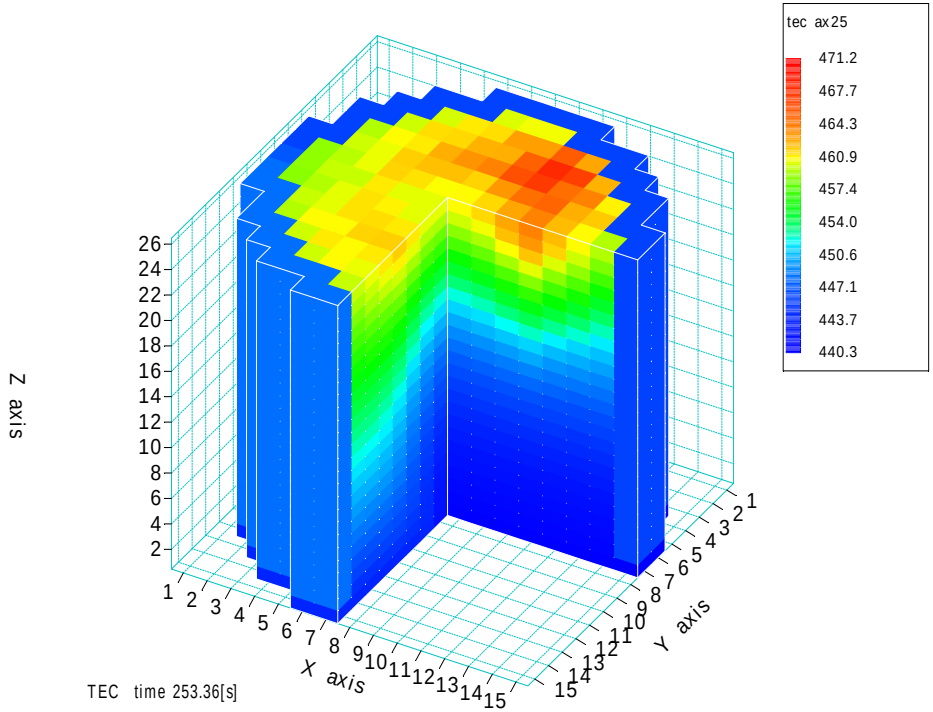


Nuklearna snaga, izbacivanje RCCA HZP



Tipični MSLB odziv





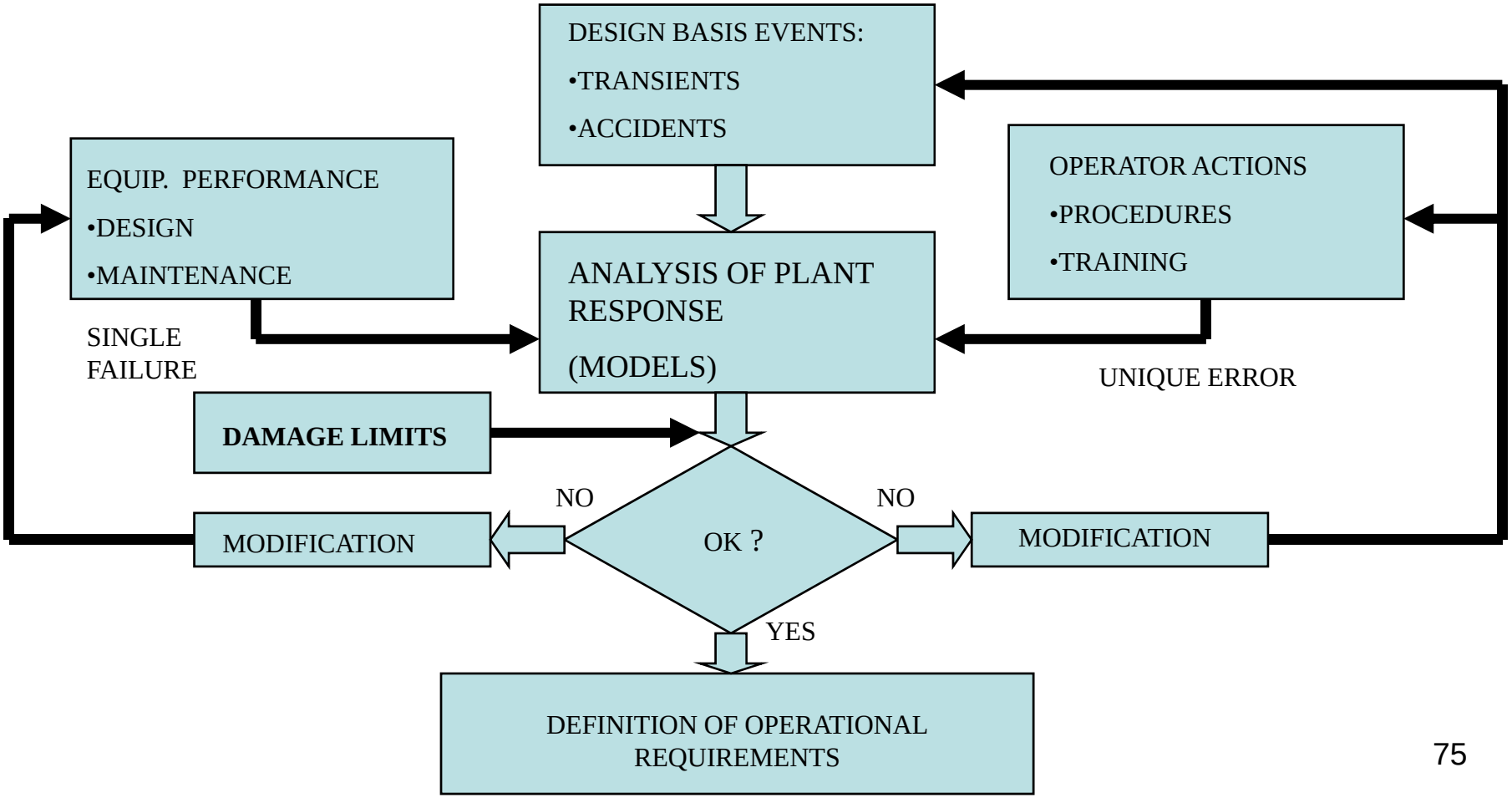
Klasifikacija događaja po posljedicama

1. No Loss of Function of Any Barrier to Radioactivity Release
2. Damage to a Small Fraction of Fuel Elements
3. Radioactivity Releases up to 10CFR100 Limits
4. Radioactivity Releases in Excess of 10CFR100 Limits

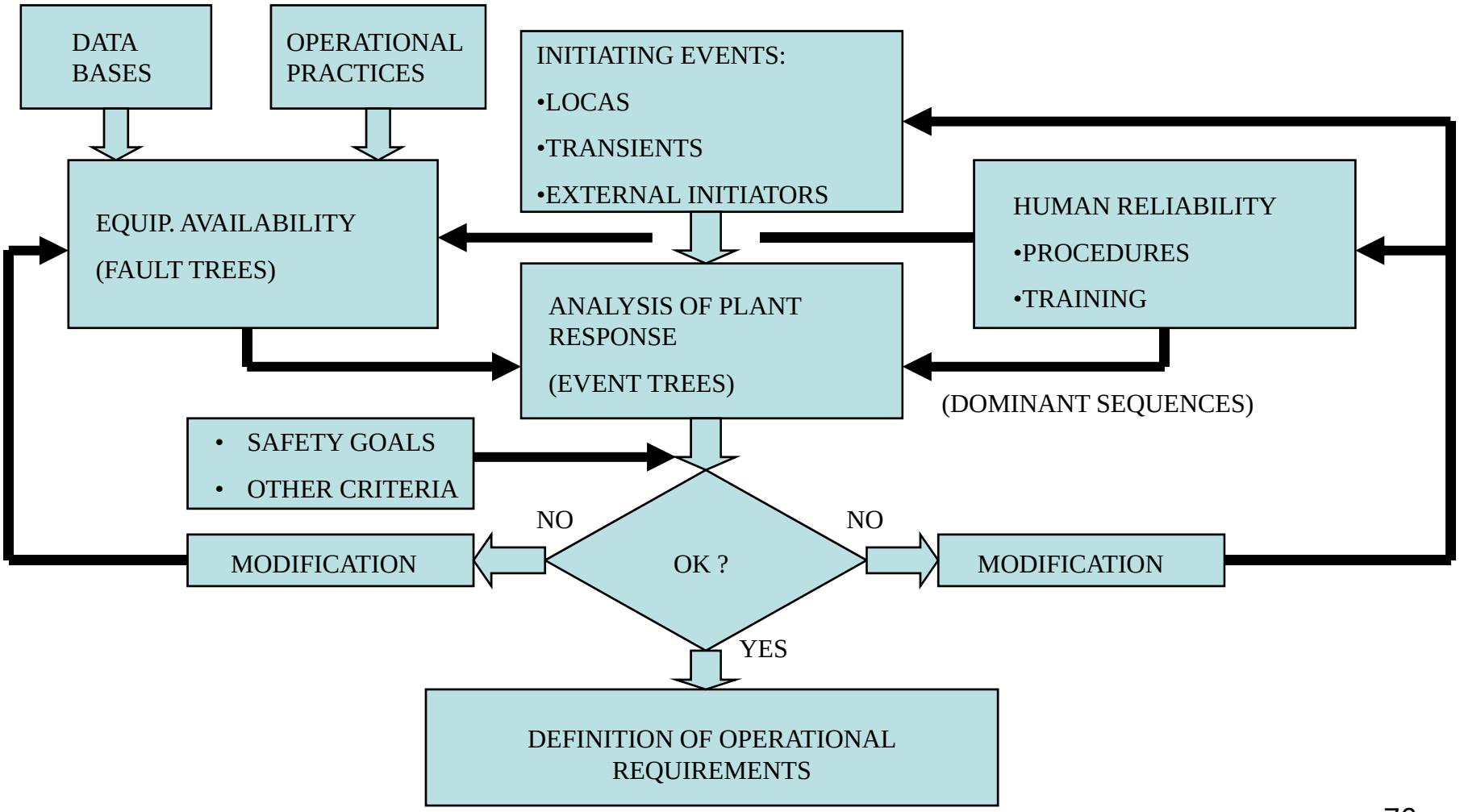
Kvantitativni kriteriji prihvatljivosti

- **FUEL TEMPERATURE**
- **FUEL ENERGY DEPOSITION**
- **CLAD HEAT TRANSFER**
- **CLAD TEMPERATURE**
- **CLAD INTEGRITY**
- **RADIOACTIVITY IN COOLANT**
- **PRIMARY OR SECONDARY SYSTEM PRESSURE**
- **CONTAINMENT PRESSURE**
- **RADIOACTIVITY IN CONTAINMENT**
- **DOSE IN CONTAINMENT**
- **DOSE TO SITE WORKERS**
- **DOSE AT SITE BOUNDARY**
- **DOSE IN LOW POPULATION ZONE**
- **DOSE TO THE PUBLIC**
- **PUBLIC HEALTH EFFECTS**

Analize sigurnosti - deterministička



Analize sigurnosti - probabilističke



Level 1 PSA
Analysis of Core Damage Frequency

- Postulated initiating events
- Specification of safety system requirements
- Analysis of the event sequence
- Safety system failure analysis
- Data
- CCF (Common Cause Failures)
- HRA (Human Risk Assessment)
- Quantification of the analysis
- Results of the analysis of core damage frequency

Level 2 PSA
Analysis of Accident Progression from Core Damage to Release of Radioactive Material

- Definition of plant damage states
- Modelling of core damage progression
- Data
- Containment performance analysis
- Source term analysis
- Results of level 2 PSA
- On-site accident management

Level 3 PSA
Analysis of the Off-site Consequences

- Source term grouping
- Atmospheric dispersion modelling
- Meteorological data
- Population, Agricultural and Economic data
- Results of the societal risk estimates
- Off-site emergency planning

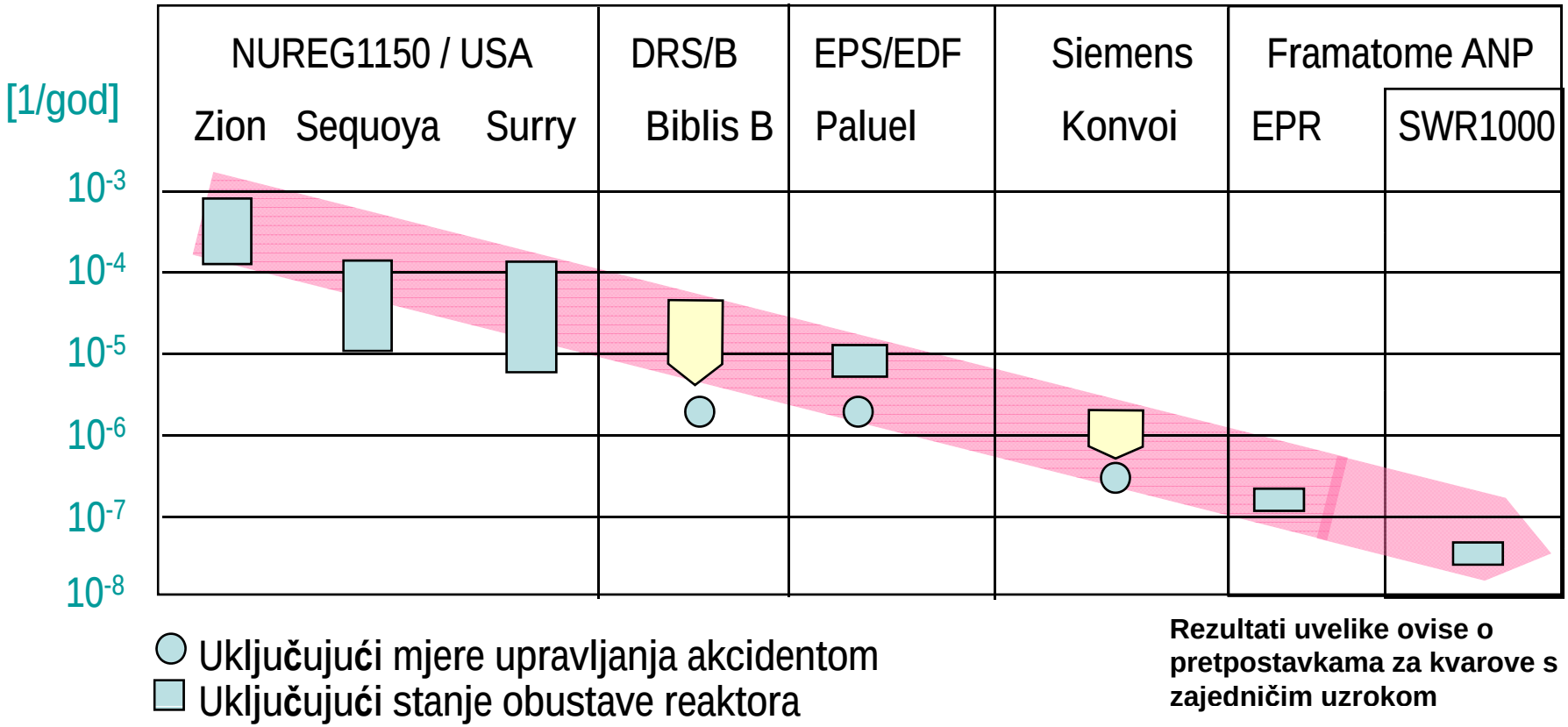
Probabilistički sigurnosni pokazatelji

- Definiranje kriterija
- Numeričke vrijednosti
- Jedna od rijetkih industrija koja je prihvatila kvantitativne pokazatelje sigurnosti

	CDF	Large releases
Existing NPP	10^{-4}	10^{-5}
New NPP	10^{-5}	10^{-6}

Inovativni reaktori

Red veličine ukupne frekvencije taljenja jezgre nuklearnih reaktora



Rezultati uvelike ovise o pretpostavkama za kvarove s zajedničim uzrokom

Rezultati proračuna vjerojatnosti oštećenja jezgre prije i poslije promjene parogeneratora i drugih tehničkih poboljšanja u NEK

Inicijalni događaji	Prije tehničkih poboljšanja (stanje 1998. god)		Poslije tehničkih poboljšanja (stanje 2000. god)	
	Vjerojatnost oštećenja jezgre po godini pogona	Doprinos vjerojatnosti oštećenja jezgre %	Vjerojatnost oštećenja jezgre po godini pogona	Doprinos vjerojatnosti oštećenja jezgre %
Interni događaji	$5{,}34 \times 10^{-5}$	24,3	$4{,}2 \times 10^{-5}$	32,8
Poplava*	$4{,}55 \times 10^{-6}$	2,1	$4{,}53 \times 10^{-6}$	3,5
Potres	$5{,}68 \times 10^{-5}$	25,8	$5{,}67 \times 10^{-5}$	44,2
Požar*	$9{,}29 \times 10^{-5}$	42,2	$1{,}25 \times 10^{-5}$	9,8
Ostali eksterni događaji	$1{,}26 \times 10^{-5}$	5,5	$1{,}26 \times 10^{-5}$	9,8
Ukupno	$2{,}2 \times 10^{-4}$	100	$1{,}28 \times 10^{-4}$	100

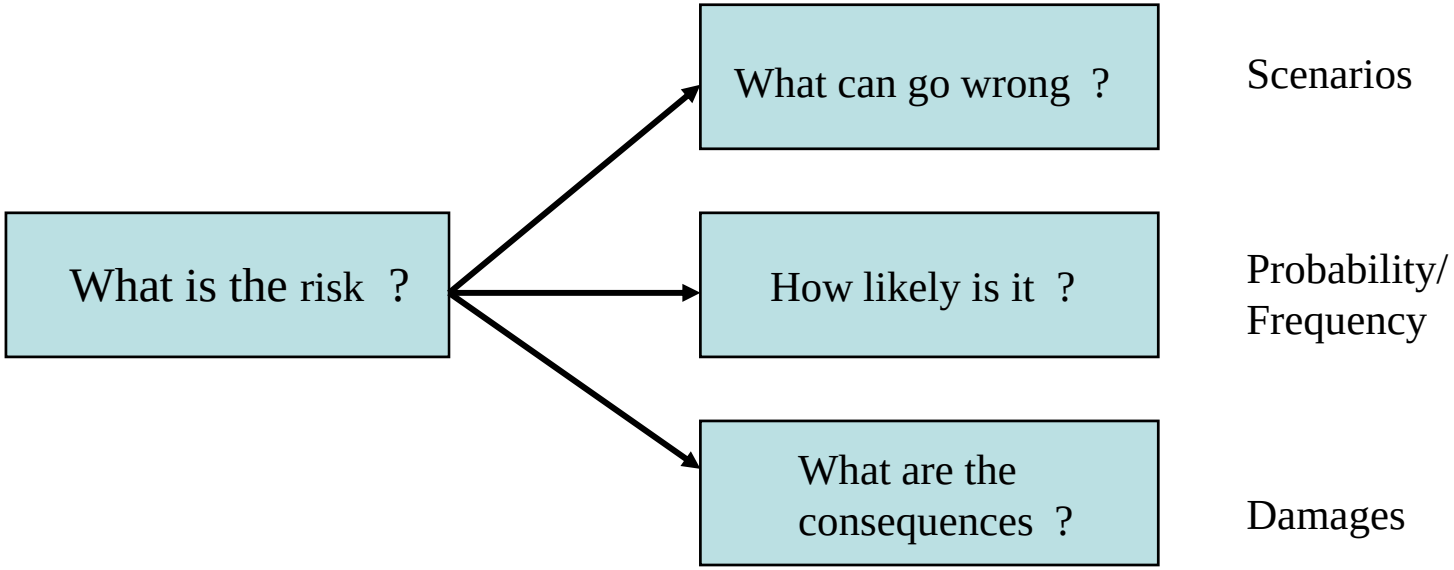
*Poplava i požar su unutarnji i vanjski događaji

Rizik vezan za nuklearne elektrane

Analize rizika

- **Determinističke i probabilističke analize su komplementarne**
- **Cilj je odrediti rizik od pogona nuklearnih elektrna**

RIZIK:



How Does Risk Assessment Work?

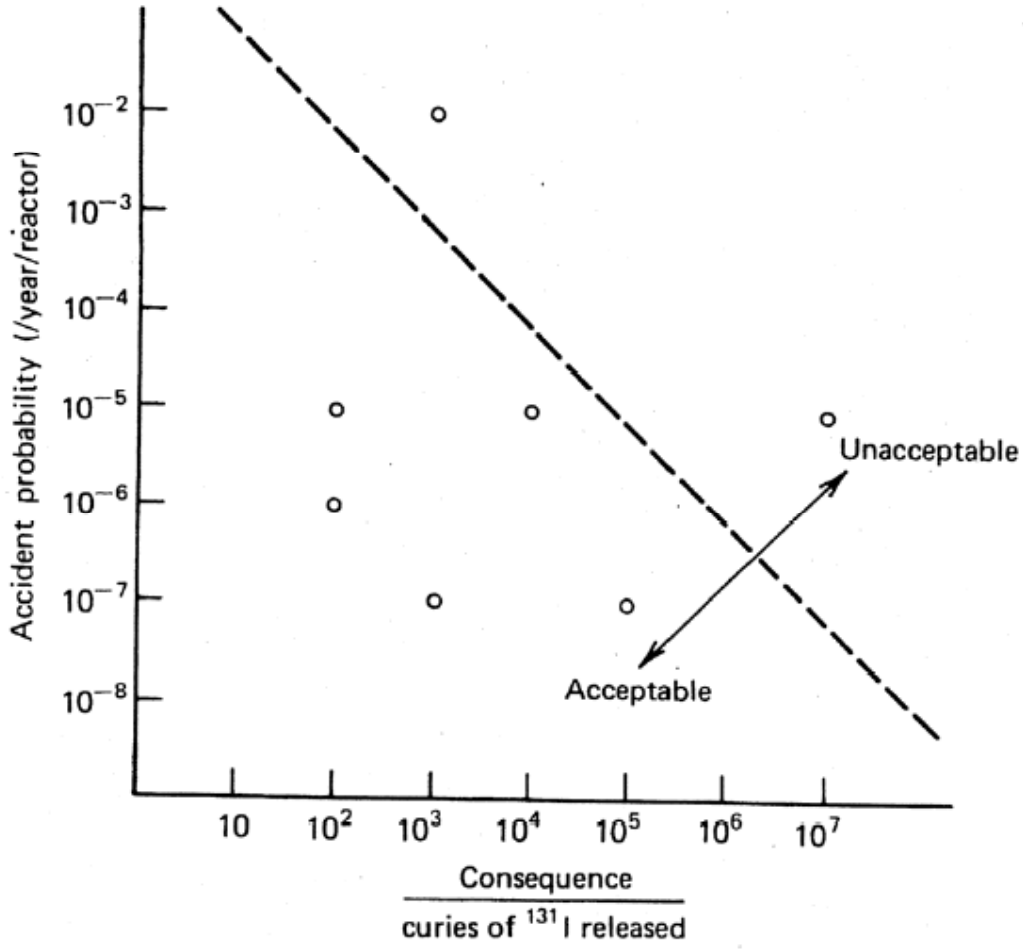
- What are the risks from driving an automobile?
- There are 15,000,000 accidents per year, 1 in 300 of which result in death, there are 250,000,000 people

$$Societal\ Risk = 15{,}000{,}000 \frac{accidents}{year} \times \frac{1}{300} \frac{deaths}{accidents} = 50{,}000 \frac{deaths}{year}$$

$$Individual\ Risk = \frac{50{,}000\ deaths / year}{250{,}000{,}000\ people} = 2 \times 10^{-4} \frac{deaths}{person \cdot year}$$

$$Lifetime\ Risk = 2 \times 10^{-4} \frac{deaths}{person \cdot year} \times 70\ years = 0.014 (1\ in\ 70)$$

Farmerov model rizika



Attitudes Towards Risk

- High Risk Activities are usually on the order of the Disease Mortality Rate :

10^{-2} deaths/(person-yr)

- Low Risk Activities are usually on the order of the Natural Hazards Mortality Rate:

10^{-6} deaths/(person-yr)

Acceptability

- Acceptability Towards Risk depends on:
  - Benefits of Activity
  - Voluntary Nature of Activity
  - Perception
  - Consequence Distribution
- Consequence Distribution:
  - Given two activities with equal risk, the public will tend to accept Low Consequence-High Frequency Events more readily than High Consequence-Low Frequency Events.

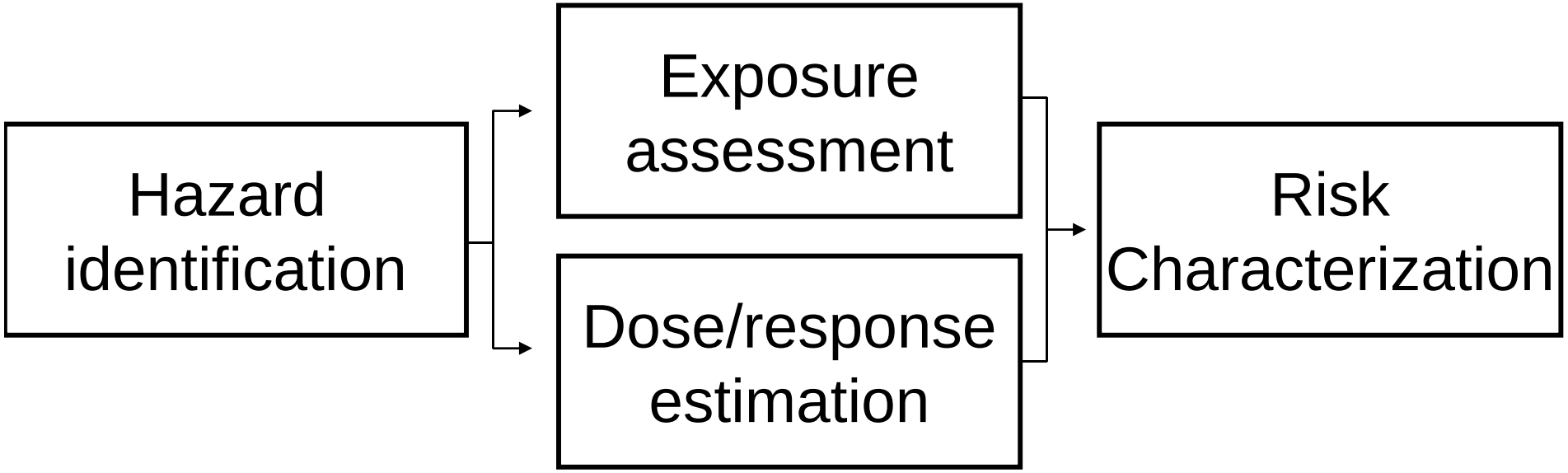
- The annual risk of *prompt* death to the most exposed member of the public due to accidents in a reactor should be small in comparison to his/her total annual risk of prompt death due to all accidents.
- The annual risk of *fatal cancer* to the most exposed member of the public due to accidents in a reactor should be small in comparison to his/her total annual risk of fatal cancer due to all causes.

- Accidents fifth leading cause of death
- Rate of 37.9 deaths / 100,000 people /a
- Average person's risk of death from an accident is 4×10^{-4} per year, so e.g.:
- **'The likelihood of a large release from a nuclear power plant in an accident should be less than 4 per 10^6 reactor years'**

- Malignant neoplasm second leading cause of death
- Rate of 182.7 deaths per 100,000 people /a
- Average person's risk of dying from cancer is 2×10^{-3} per year (~ 15% over 75-years)
  - 100 person-Sv $\Rightarrow$ ~5 fatal cancers
  - "Averaged" risk of 5×10^{-2} fatal cancers per Sv
  - Equivalent dose is 0.04 Sv per year per person

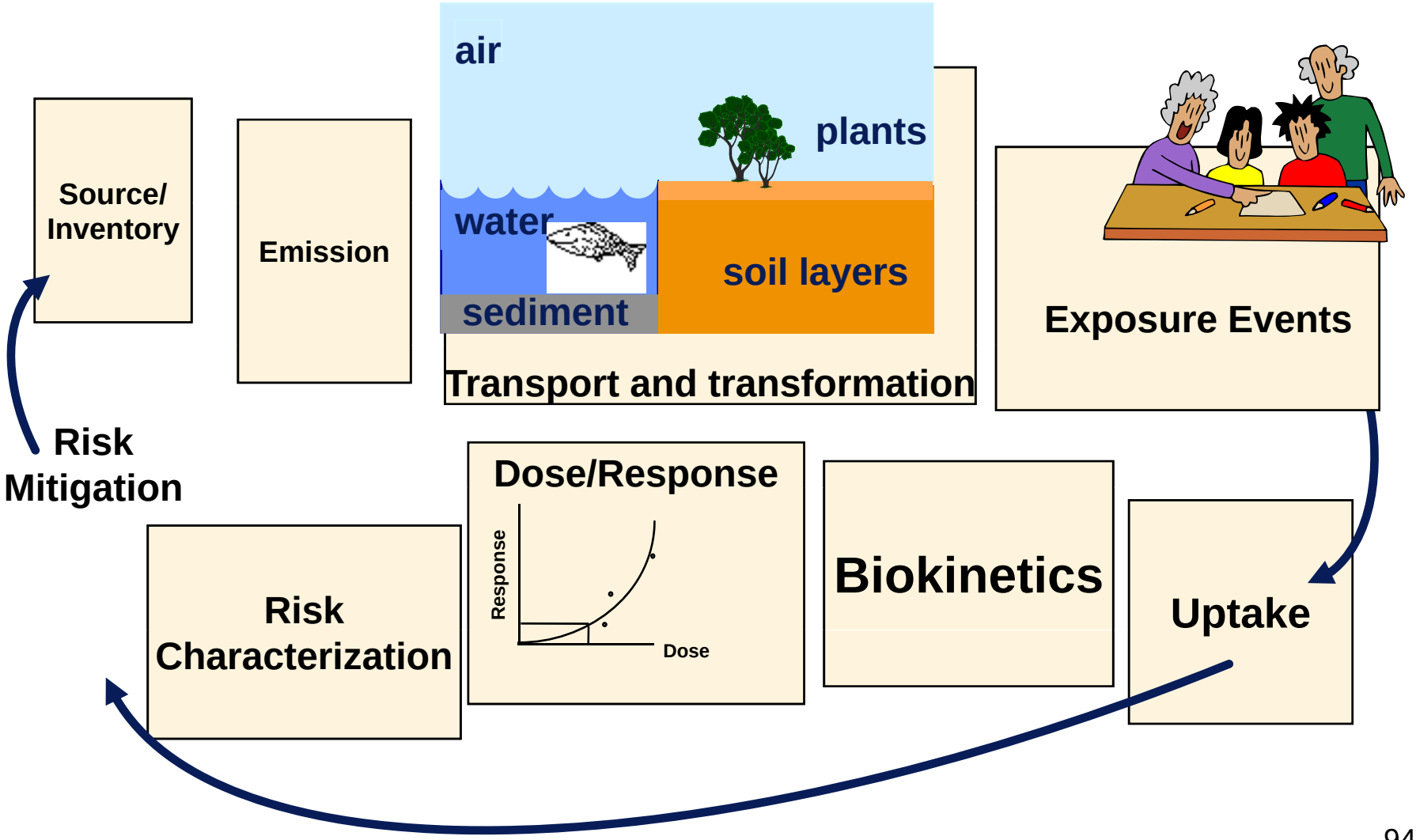
- **Maximum time-averaged individual dose from accidents should be less than 0.4 mSv per year, averaged over a group of people**
  - ~ 40% natural background radiation
  - Should nuclear power be 'safer' than background radiation?
- Requires summation of all accidents

Risk Assessment



- Hazard identification uses toxicology (cell, tissue and animal tests) and epidemiology (population data and field samples)
- Exposure assessment includes determination of sources, environmental concentrations, exposure, dose, and uncertainties

Framework for Risk Assessment



Rezultati studije sigurnosti WASH 1400

- **Studija WASH 1400 usporedila je rizik stanovništva koje živi 30 km oko 66 USA lokacija od rada 100 nuklearnih elektrana na tim lokacijama s rizikom kojem je to isto stanovništvo (oko 15 milijuna ljudi) izloženo zbog drugih razloga.**
- **Očekivani godišnji broj ranih smrtnih slučajeva i bolesti 15 milijuna stanovnika koji žive na 30 km od lokacija američkih nuklearnih elektrana.**

Rezultati studije sigurnosti WASH 1400

Vrsta akcidenta	Rani smrtni slučajevi	Povrede
automobilske nesreće	4 200	375 000
padovi	1 500	75 000
požari	560	22 000
udari struje	90	?
udari gromova	8	?
pogon 100 nuklearnih reaktora	0,3	6

Rezultati studije sigurnosti WASH 1400

Opći zaključci koji slijede iz studije jesu:

- **akcidenti koji vode do oštećenja jezgre bez gubitka integriteta zaštitne posude vrlo malo utječu na okolinu,**
- **rizici od reaktorskih nesreća kojima je izloženo stanovništvo manji su od rizika koji nastaju zbog drugih uzroka u svakodnevnom životu,**
- **vjerojatnost nastanka reaktorskih akcidenata mnogo je manja od vjerojatnosti nastanka drugih nezgoda koje daju slične posljedice.**

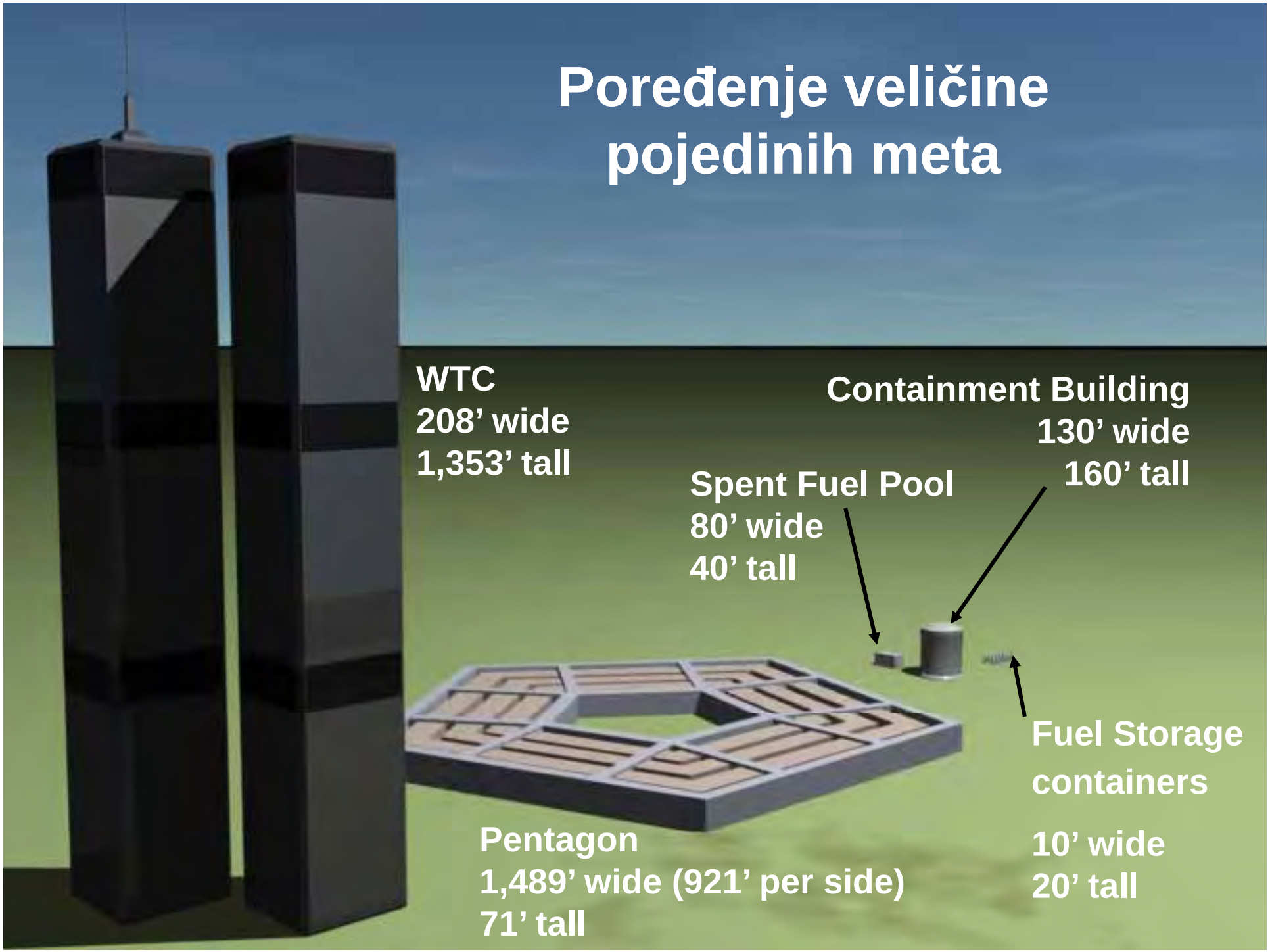
Njemačka studija rizika

- **Njemačka studija rizika (Deutsche Rizikostudie Kernkraftwerke), izrađena je u dvije faze (faza A 1979. godine i faza B 1989. godine).**
- **U Njemačkoj su analizirani rizici stanovništva od rada 25 nuklearnih elektrana na 19 lokacija.**
- **Metoda primijenjena pri razradi njemačke studije rizika slična je metodi iz studije WASH 1400.**
- **Značajno je primijetiti da rezultati dobiveni u njemačkoj studiji rizika ne odstupaju bitno od onih u studiji WASH 1400.**

Rezultati njemačke studije rizika
Godišnji rizik od fatalne nesreće za milijun stanovnika u blizini nuklearnih elektrana u Njemačkoj

Uzrok i tip akcidenta	Prosječni godišnji broj ranih smrtnih slučajeva na milijun stanovnika
rad u rudnicima	540
rad u zdravstvu	40
nesreće na radu (prosječno)	130
rad u domaćinstvu i rekreacijske aktivnosti	230
vožnja automobilom (75 min. dnevno)	240
vožnja avionom (1 sat tjedno)	50
udari struje	4
udari groma	0,6
rana smrt zbog nuklearnog akcidenta	0,01
smrt od raka zbog izlaganja zračenju kod nuklearnog akcidenta	0,2
smrt od raka zbog uzroka koji nisu vezani uz rad nuklearnih elektrana	2700

Fizička sigurnost objekta i terorizam


Poređenje veličine pojedinih meta
WTC
208’ wide
1,353’ tall
Containment Building
130’ wide
160’ tall
Spent Fuel Pool
80’ wide
40’ tall
Fuel Storage containers
10’ wide
20’ tall
Pentagon
1,489’ wide (921’ per side)
71’ tall

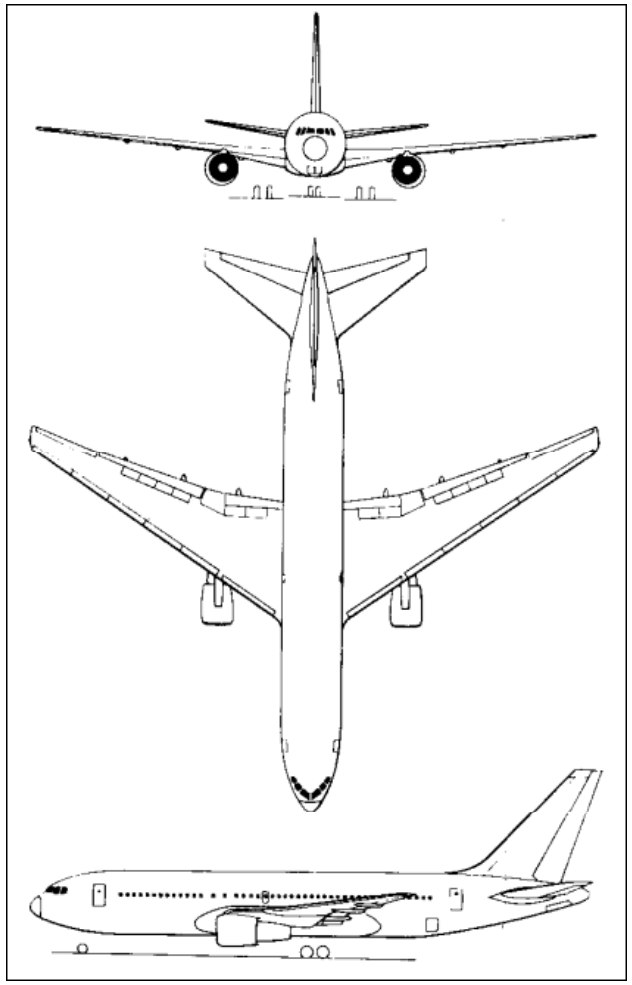
Rezultat studije o padu/udaru aviona

Pretpostavke:

- Veliki putnički avion pun goriva
- Optimalni kut udara
- Optimalna brzina

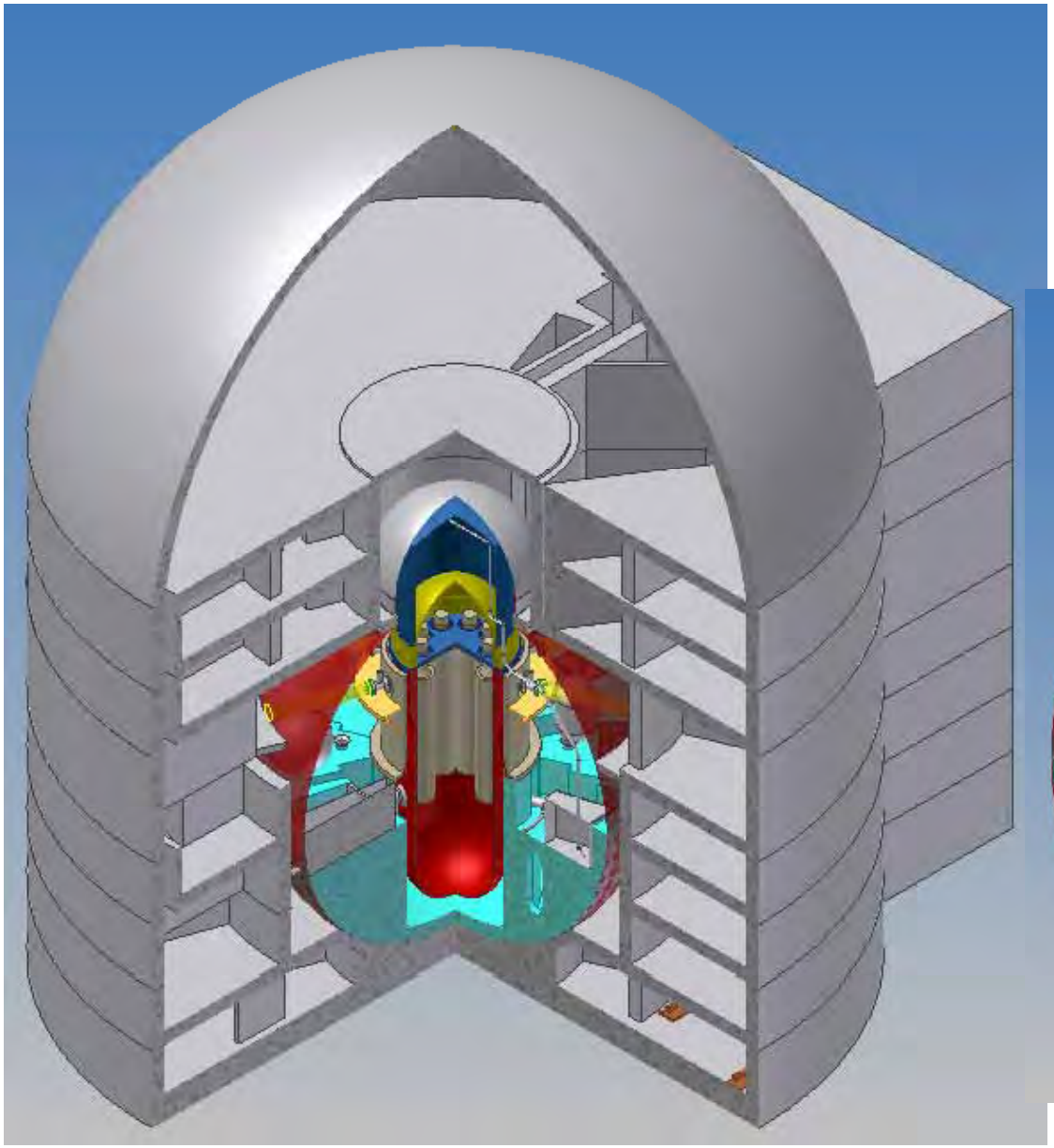
Rezultati – nema oštećenja:

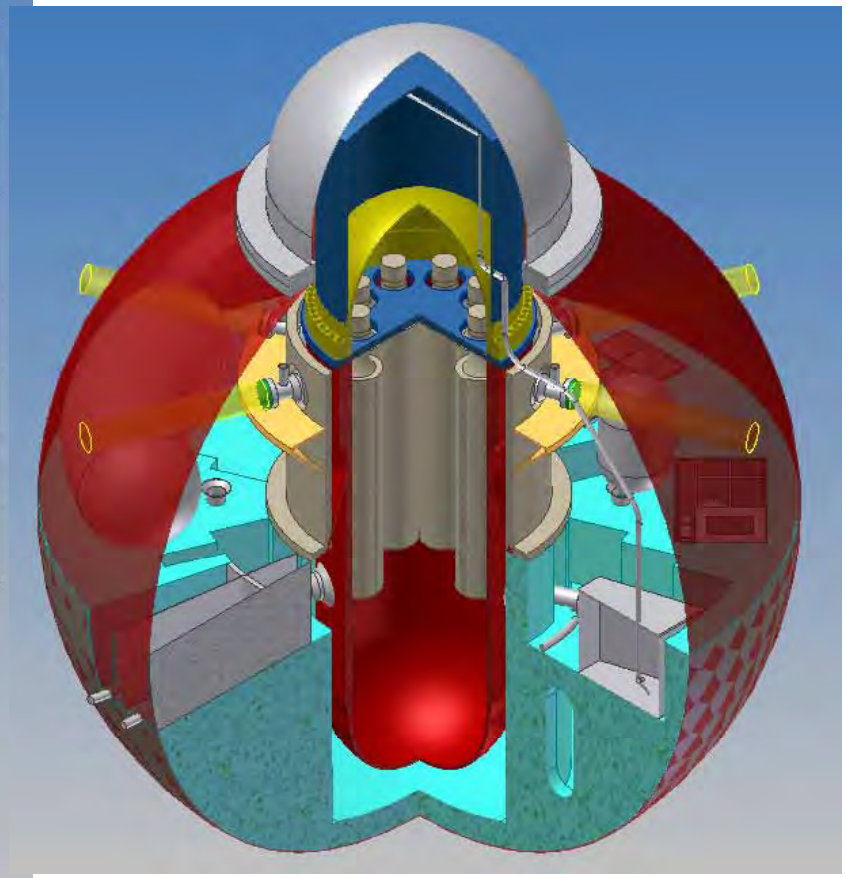
- Kontejnment
- Zgrada za istrošeno gorivo
- Kontejner za privremeno spremanje/transport goriva



Razmještaj objekata na lokaciji NE

IRIS elektrana





Fizička sigurnost objekta
Owner-
Controlled Area
Protected Area
Double Fence
Protected
Area
Vital Area
Access Control Points

Nuklearne nesreće

Nuklearne nesreće

- **Da** li su moguće?
- **Da** li ih je bilo?
- Kako je do njih došlo?
  - Greške projektu
  - Greške u procedurama
  - Greške u treningu
  - Greške operatora u izvedbi
- Koji je dugoročni efekt?
  - Nuklearne elektrane su potvrdile loš glas koji prati nuklearnu energiju vezano za njene vojne početke
  - Unaprijedile su sigurnost (bolji projekti, procedure, školovanje, planiranje)

Teške reaktorske nesreće eksperimentalni

Reactor	Date	Immediate Deaths	Environmental effect	Follow-up action
NRX, Canada (experimental, 40 MWt)	**1952**	**Nil**	**Nil**	**Repaired (new core) closed 1992**
Windscale-1, UK (military plutonium-producing pile)	**1957**	**Nil**	**Widespread contamination. Farms affected (c 1.5 x 10^{15} Bq released)**	**Entombed (filled with concrete) Being demolished.**
SL-1, USA (experimental, military, 3 MWt)	**1961**	**Three operators**	**Very minor radioactive release**	**Decommissioned**
Fermi-1 USA (experimental breeder, 66 MWe)	**1966**	**Nil**	**Nil**	**Repaired, restarted 1972**
Lucens, Switzerland (experimental, 7.5 MWe)	**1969**	**Nil**	**Very minor radioactive release**	**Decommissioned**

Teške reaktorske nesreće komercijalni

Reactor	Date	Immediate Deaths	Environmental effect	Follow-up action
Browns Ferry, USA (commercial, 2 x 1080 MWe)	**1975**	**Nil**	**Nil**	**Repaired**
Three-Mile Island-2, USA (commercial, 880 MWe)	**1979**	**Nil**	**Minor short-term radiation dose (within ICRP limits) to public, delayed release of 2 x 10^{14} Bq of Kr-85**	**Clean-up program complete, in monitored storage stage of decommissioning**
Saint Laurent-A2, France (commercial, 450 MWe)	**1980**	**Nil**	**Minor radiation release (8 x 10^{10} Bq)**	**Repaired, (Decomm. 1992)**
Chernobyl-4, Ukraine (commercial, 950 MWe)	**1986**	**31 staff and firefighters**	**Major radiation release across E.Europe and Scandinavia (11 x 10^{18} Bq)**	**Entombed**
Vandellos-1, Spain (commercial, 480 MWe)	**1989**	**Nil**	**Nil**	**Decommissioned**

Nesreća u TMI-2

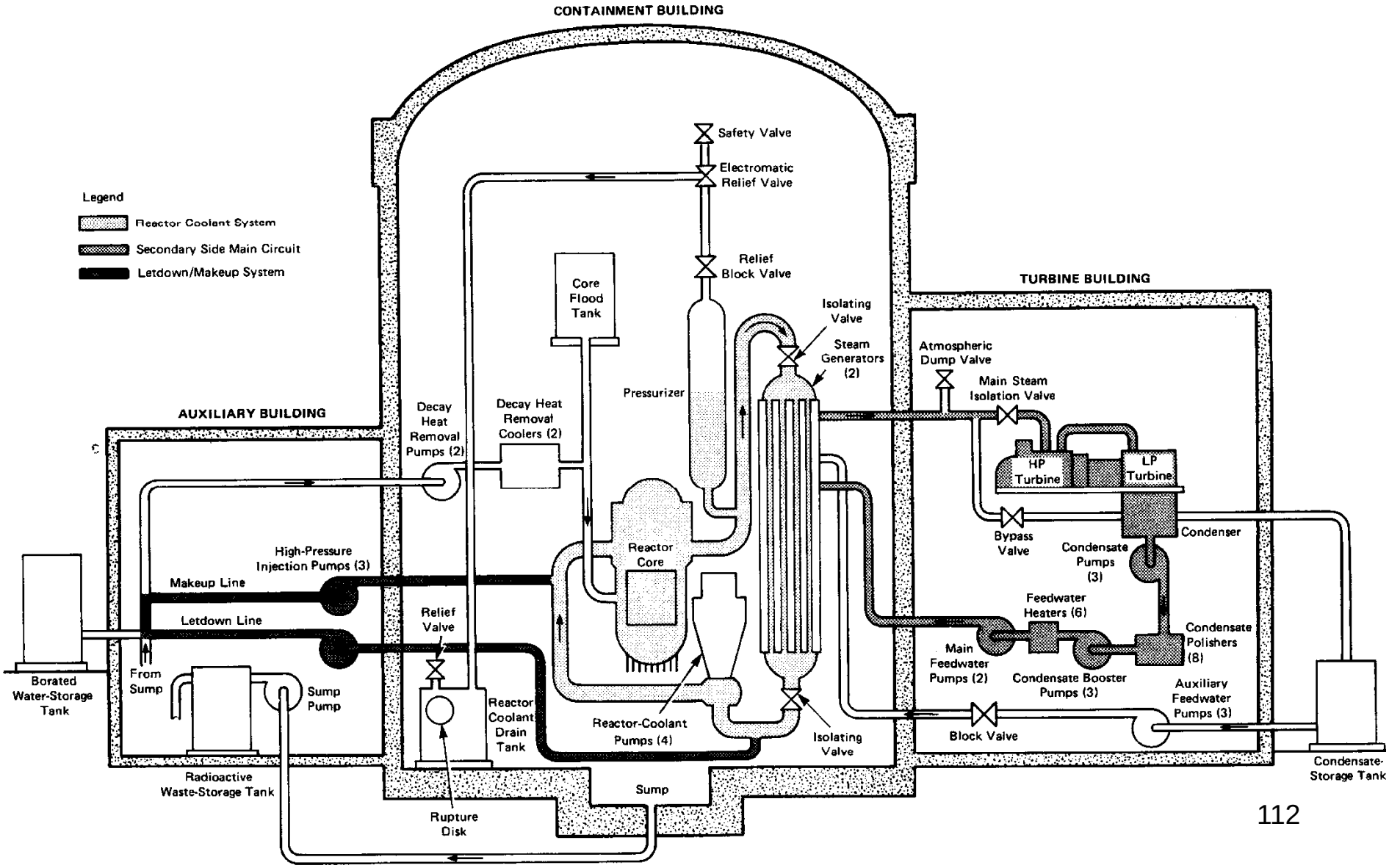
March 28, 1979, 4:00 am local time

Nesreća u NE Otok tri milje TMI-2

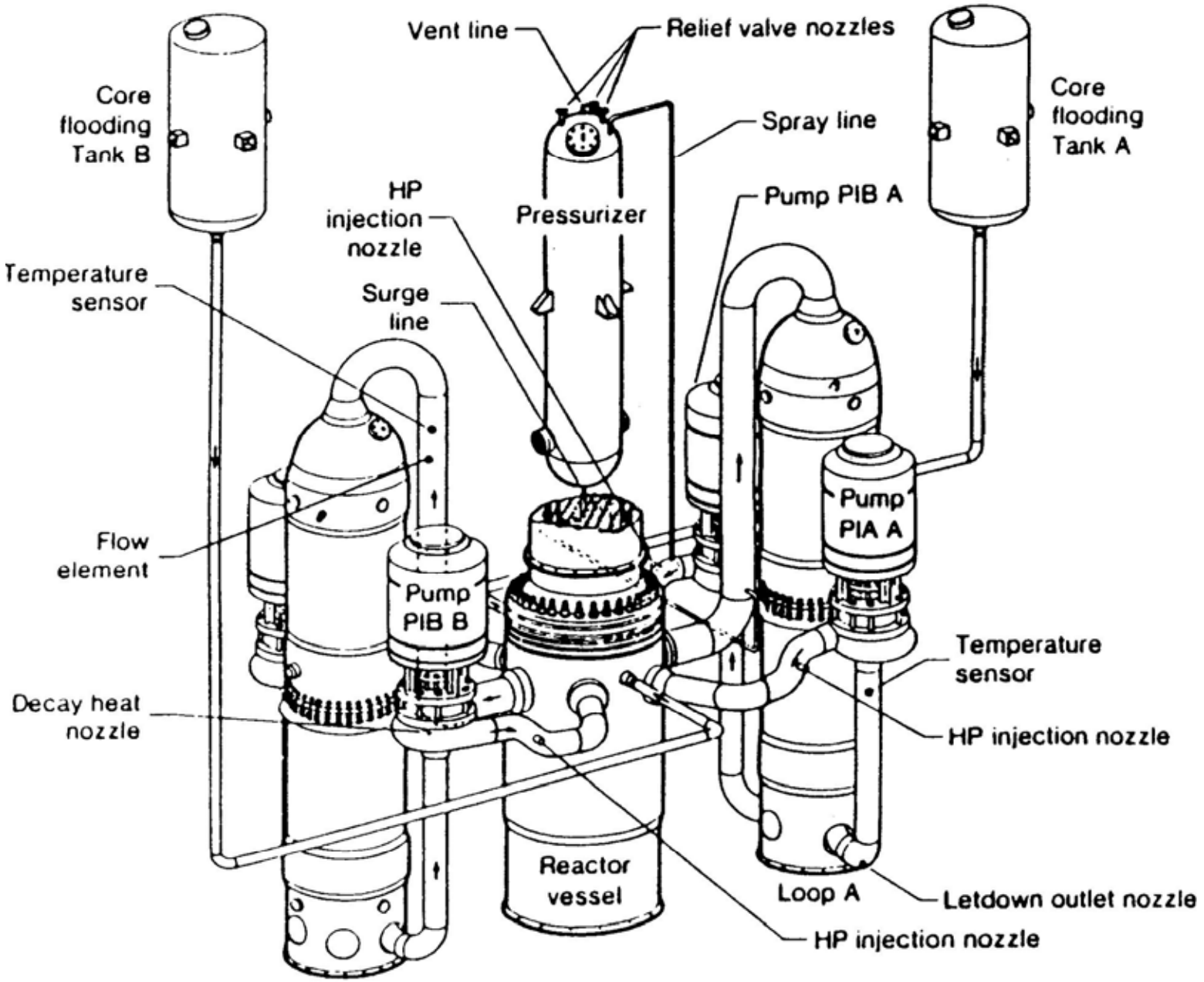
Sekvenca događaja

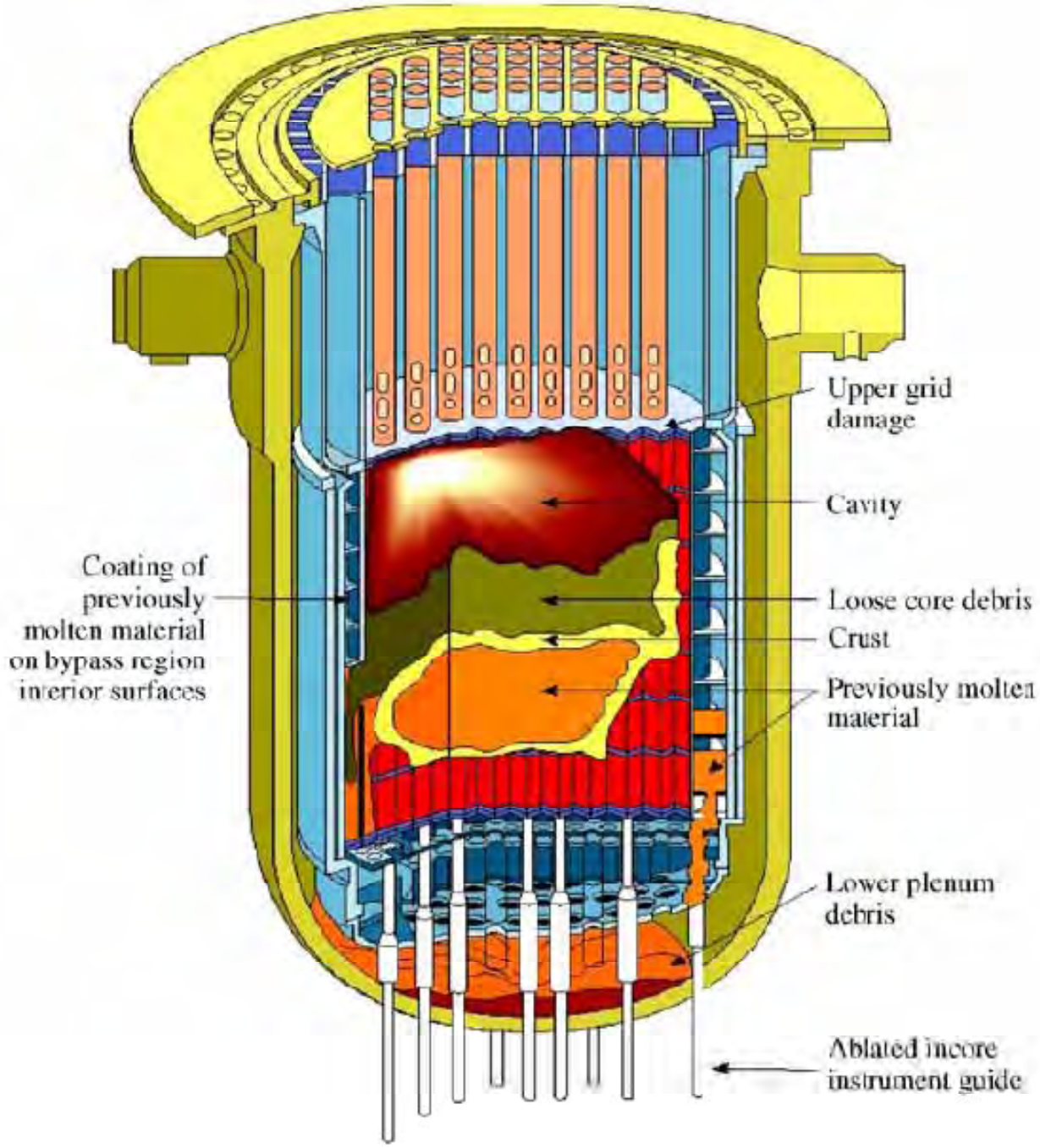
1. Kvar sustava za demineralizaciju pojne vode parogeneratora
2. Ispad pumpi pojne vode
3. Ventil sustava pomoćne pojne vode ostao zatvoren što operateri nisu primijetili
4. Gubitak vode na sekundarnoj strani parogeneratora
5. Pregrijavanje primarnog kruga, porast tlaka, obustava reaktora
6. Otvaranje rasteretnih ventila tlačnika – ostali otvoreni!
7. Primarna voda se gubi, tlak pada, isparavanje vode
8. Operateri zaustavljaju primarne pumpe radi zaštite pumpi
9. Formiranje parnog mjehura u jezgri koji blokira protok vode kroz reaktor i potiskuje vodu u tlačnik
10. Operateri zaustavljaju rad pumpi sustava za zaštitno hlađenje jezgre
11. Pregrijavanje jezgre

Dijelovi NE TMI-2
bitni za razumijevanje nesreće



Reaktorski sistem NE TMI-2





Rezultat – oštećenje jezgre

Izvor topline:

-Ostatna toplina
-egzotermna reakcija oksidacije

Trajanje akcidenta:
16 sati

Nesreća u NE Otok tri milje TMI-2

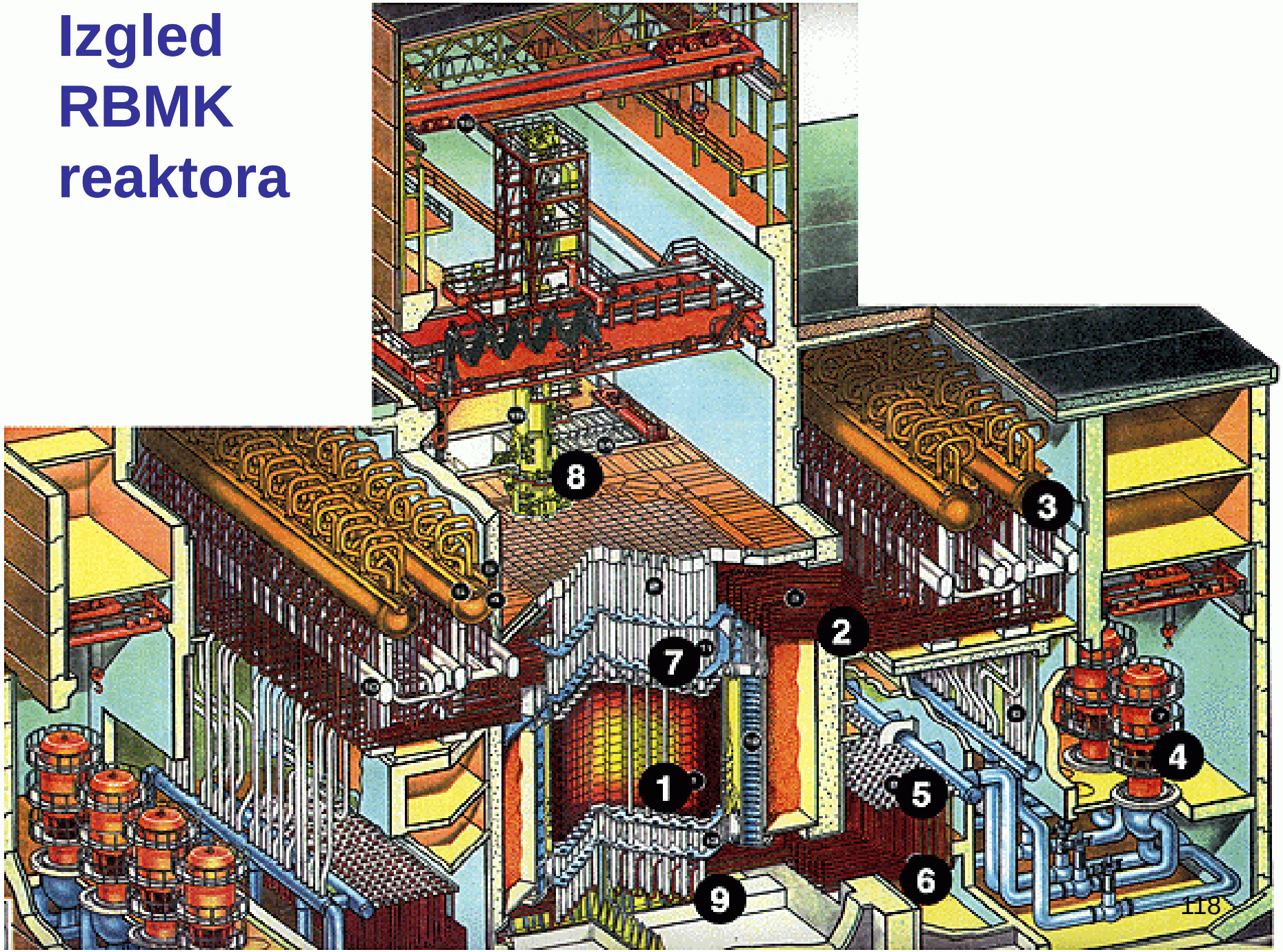
- Nesreća na elektrani TMI-2 ukazala je na nedostatke u:
  - izvedbi elektrane
  - procedurama
  - obuci operatera
- Postalo je očigledno da do oštećenja jezgre može doći i kod malog ispuštanja iz primarnog sustava
- Znatno pooštreni sigurnosni zahtjevi ugradnjom novih tehničkih sustava i školovanjem operatera

Akcident u Černobilu

- **NE Černobil je imala RBMK-1000 reaktor.**
- **Kao posljedica neoprezno izvedenog eksperimenta na jedinici 4, 26.04.1986., brzi porast snage izazvao je topljenje goriva i razaranje reaktorske zgrade. Slijedile se naknadne eksplozije, pare i vodika te požar grafita.**
- **Radioaktivni materijal je oslobađan u atmosferu tijekom 10 dana.**

NE Černobil

Izgled RBMK reaktora



RBMK-1000 reaktor

Prednost:

- izmjena goriva tijekom pogona – visoka raspoloživost, te mogućnost reguliranja odgora goriva u pojedinim rashladnim kanalima bez potrebe za obustavom pogona

Nedostaci:

- nema zaštitne zgrade
- pozitivan temperaturni koeficijent šupljina (najniža dopuštena termička snaga oko 22 % ukupne snage)
- sporo kretanje regulacijskih šipki (voda u kanalima jezgre ograničava njihovu brzinu kretanja)
- regulacijske šipke u svojem gornjem i donjem dijelu sadrže grafit umjesto apsorpcijskog materijala

Nesreća u NE Černobil

Eksperiment – da li nakon gubitka vanjskog napajanja električnom energijom turbina u zaustavljanju može proizvesti dovoljno električne energije za napajanje sustava za zaštitno hlađenje jezgre prije starta dizel generatora

- plan je bio izvesti eksperiment na 30 % snage (nema tripa reaktora kako bi operateri imali mogućnost ponoviti eksperiment)
- eksperiment se trebao odnositi na ne-nuklearni dio elektrane
- nije bilo koordinacije između osoblja zaduženog za eksperiment i osoblja zaduženog za sigurnost elektrane

Tijek događaja 25.04.1986.

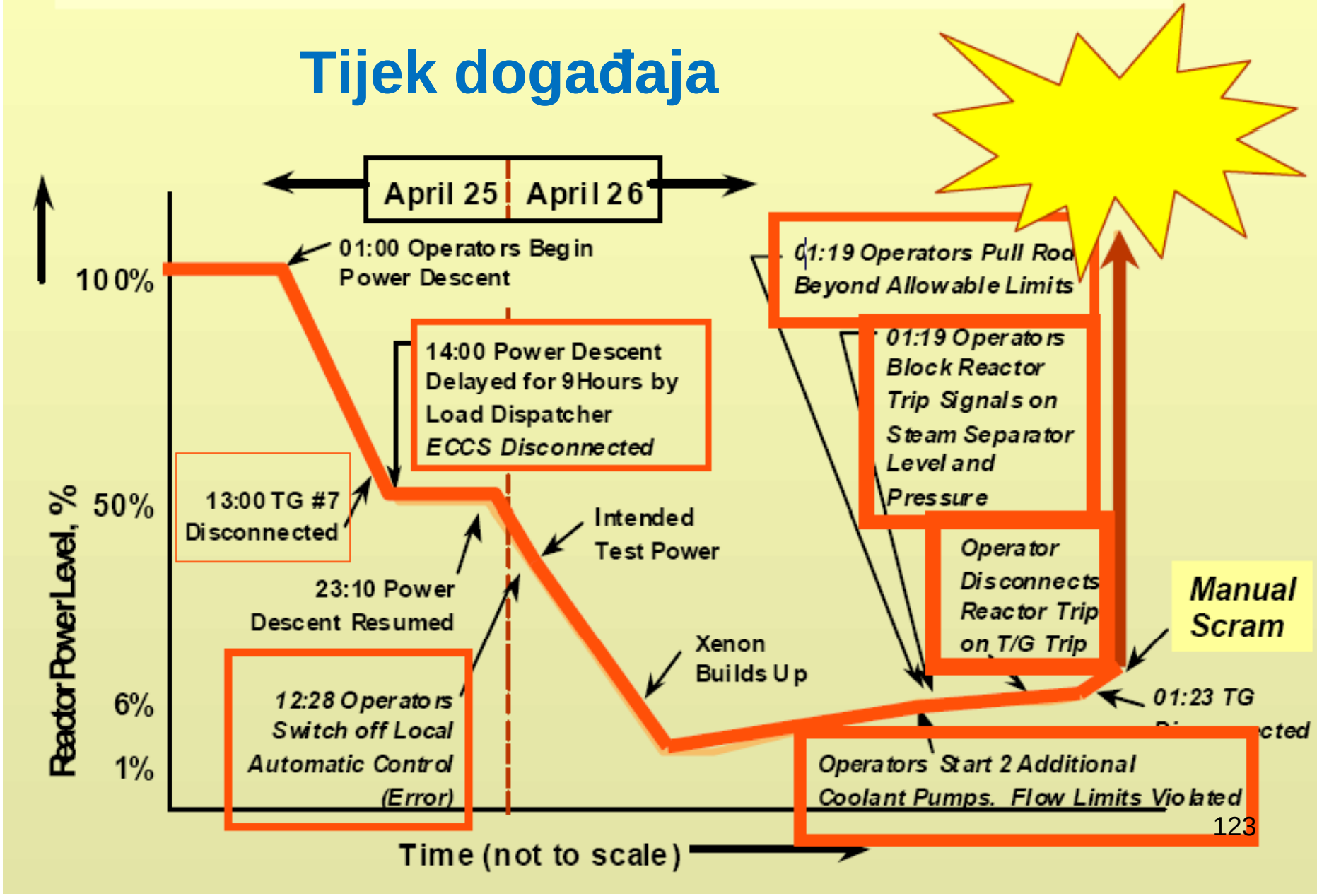
- 01:06 počinje gašenje reaktora, postepeno smanjivanje snage, početak testa
- 03:47 zaustavljeno gašenje na 1600 MW(t), zahtjev kijevskog operatera da elektrana ostane na snazi
- 14:00 izoliran ECCS

Tijek događaja 26.04.1986.

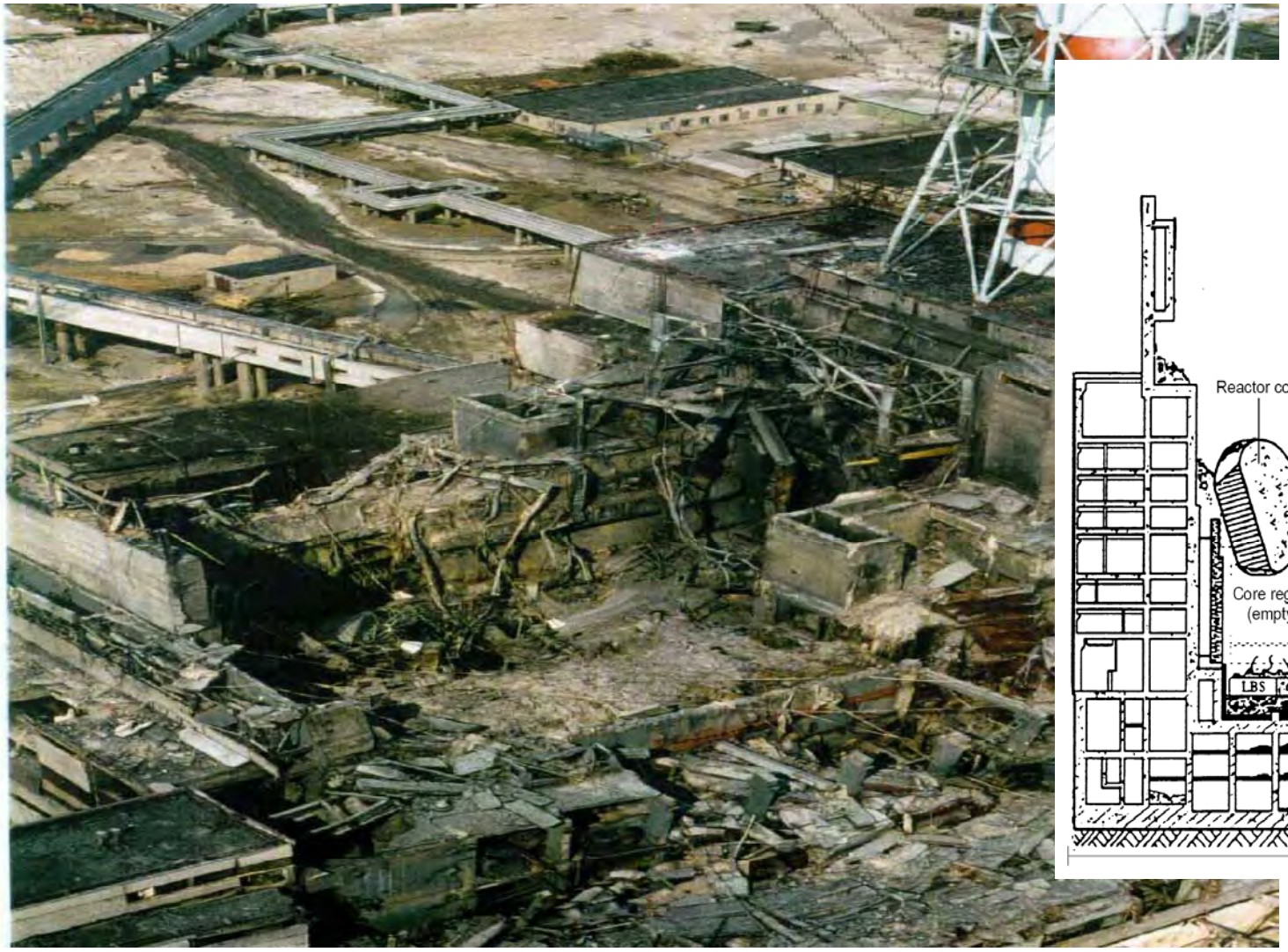
- 01:23:47 snaga reaktora na 30000 MW(t)
  - tlak pare ubrzano raste – prva eksplozija
  - razorena reaktorska zgrada – jezgra izložena atmosferi
  - taljenje gorivih elemenata
  - reakcija goriva i obloge – vodik – druga eksplozija
  - vrući grafit počinje gorjeti u dodiru s kisikom iz atmosfere

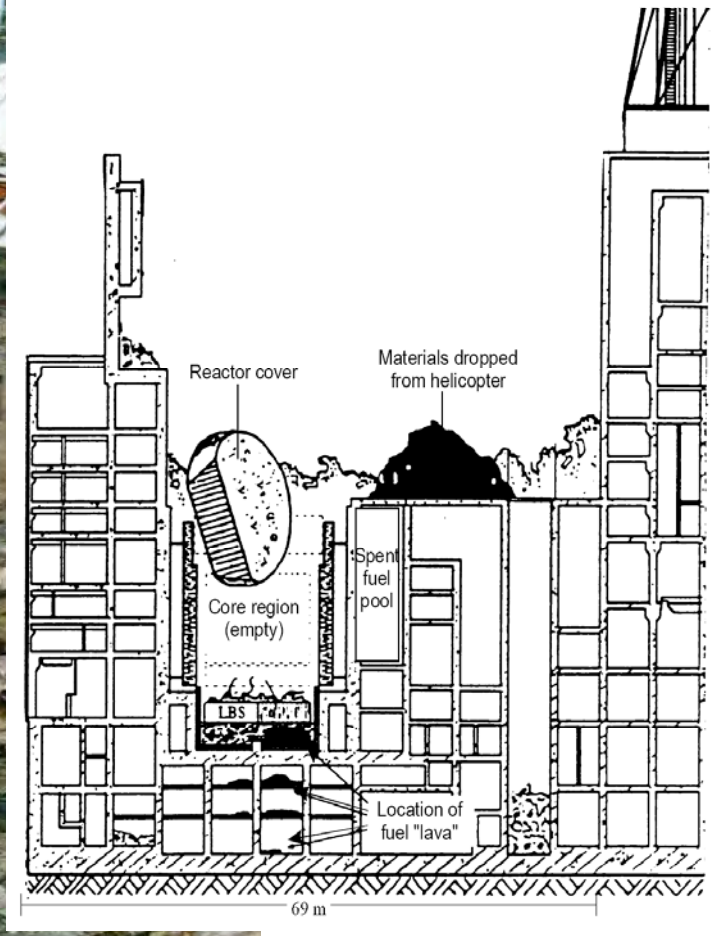
Events Leading to Accident

Tijek događaja



Posljedice razaranja





Nesreća u NE Černobil - uzroci

- primarni uzrok (ljudska pogreška) - serija narušavanja instrukcija i operativnih procedura
- sekundarni uzrok (pozitivni koeficijent reaktivnosti i ostali nedostaci izvedbe elektrane)

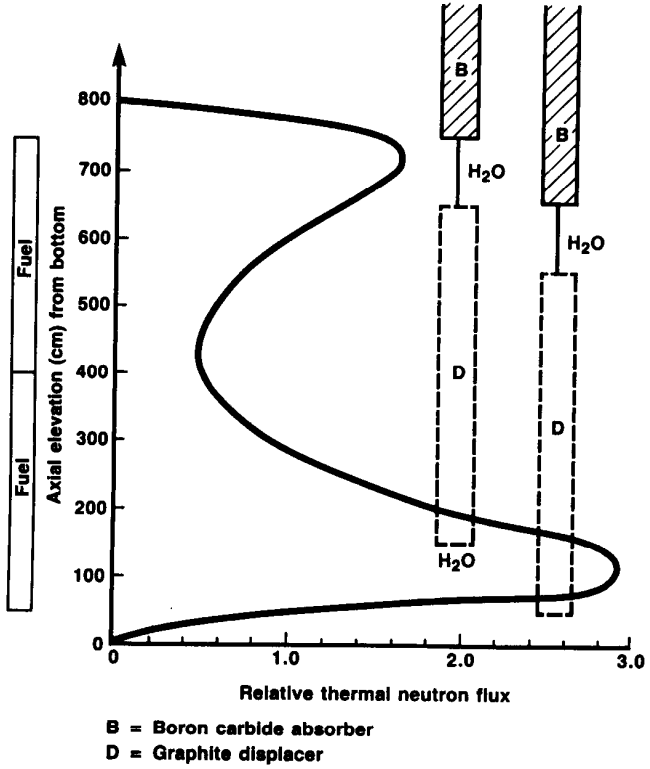
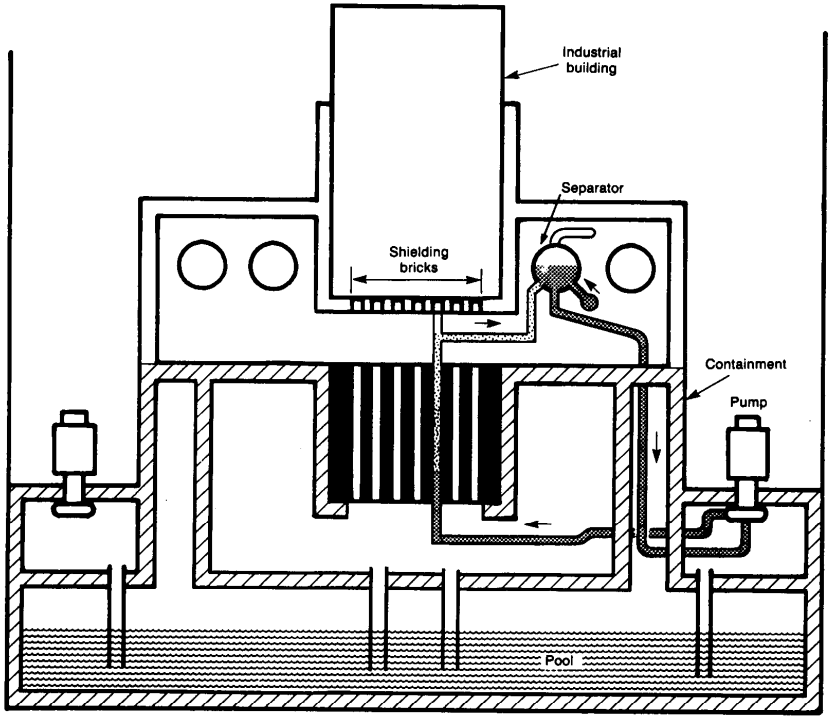


Figure 5 Axial flux distribution preceding accident.



Nesreća u NE Černobilj - posljedice

•31 žrtva neposredno nakon nesreće

•134 su liječena od posljedica akutnog rdijacijskog sindroma

• Prema IAEA dokumentu INSAG-1 može se računati sa 170 dodatnih smrtnih slučajeva od raka

• procijenjeno povećanje rizika od smrtnosti zbog raka stanovništva zemalja zahvaćenim radioaktivnim oblakom varira od 0,03 % do 0,15 % u odnosu na neozračenu populaciju

• nesreća je imala ogroman negativan utjecaj na razvoj nuklearne energetike, iako RBMK nije relevantan za današnju nuklearnu energetiku

Chernobyl Accident Consequences
Actual Health Consequences

Population	Number
• Early fatalities (non-radiation)	2 (immediate)
• Early fatalities (radiation)	28 (within 4 m)
• Late adult fatalities (radiation)	19 (as of 9/05)
• Late child fatalities (radiation)	9* (as of 9/05)
• Clinical psychological effects	~ 5,000,000

*All thyroid cancer deaths in population of 4000 identified and treated cases.

Utjecaj na zdravlje - NGO

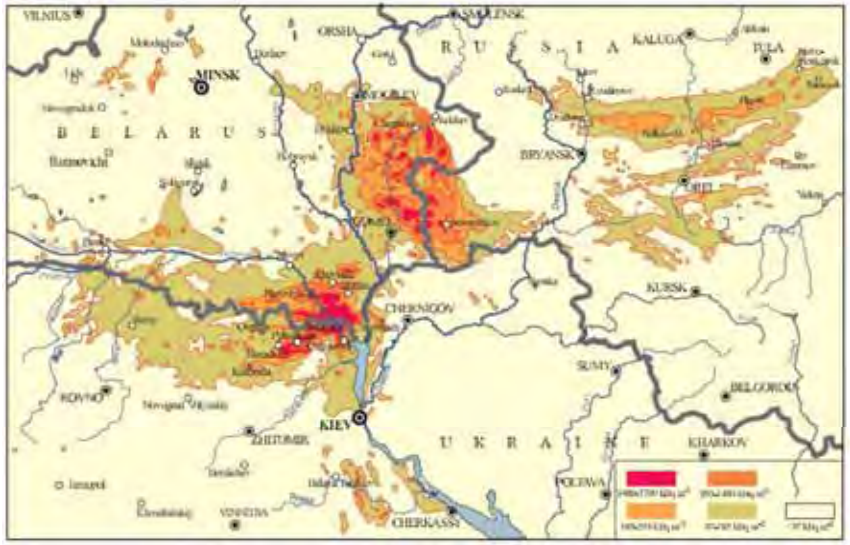
- 31 neposredna žrtva
- Približno 2500 dodatnih smrti vezano za akcident
- Značajan porast raka štitne žljezde
- Učestalost raka štitne žljezde u populaciji do 15 godina povećana od 4 do 6 u milion stanovnika (1981-1985) na 45 u milion stanovnika (na nivou cijele Ukrajine) u razdoblju 1986 do 1997
- 64% slučajeva zabilježeno u najzagađenijim područjima.

Nezdravstveni utjecaj na lokalnu zajednicu

- 116,000 ljudi evakuirano od 1990 do 1995 i 210,000 relocirano.
- Promjene u osnovnoj infrastrukturi
- Manjak električne energije
- Poljoprivredne aktivnosti znatno smanjene s direktnim utjecajem na prihod stanovništva.

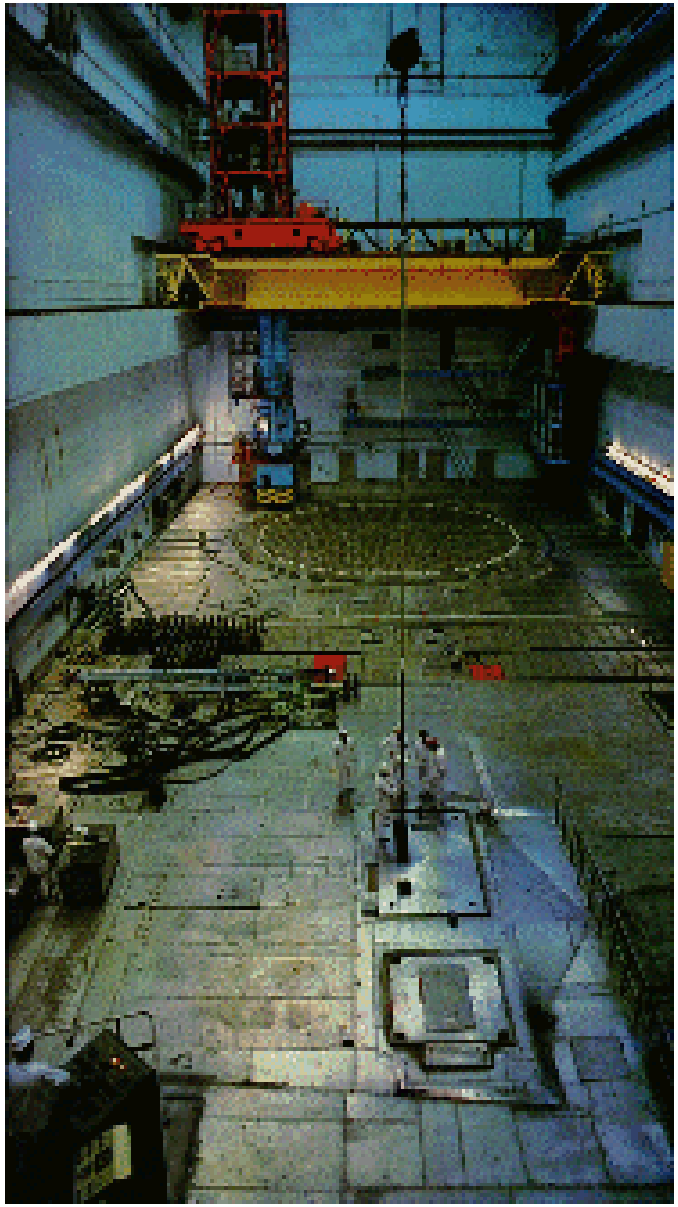
Utjecaj na okoliš

- Radioaktivna kontaminacija u dobrom dijelu Europe, u konačnici gotovo cojela sjeverna hemisfera.
- U lokalnom ekosustavu (10 km radius) promjene na stablima, smrt malih sisavaca.
- Okoliš se oporavlja ali na duge staze mogući su genetski efekti.



Cs-137

Unit 1
Unit 2
Unit 3
Unit 4

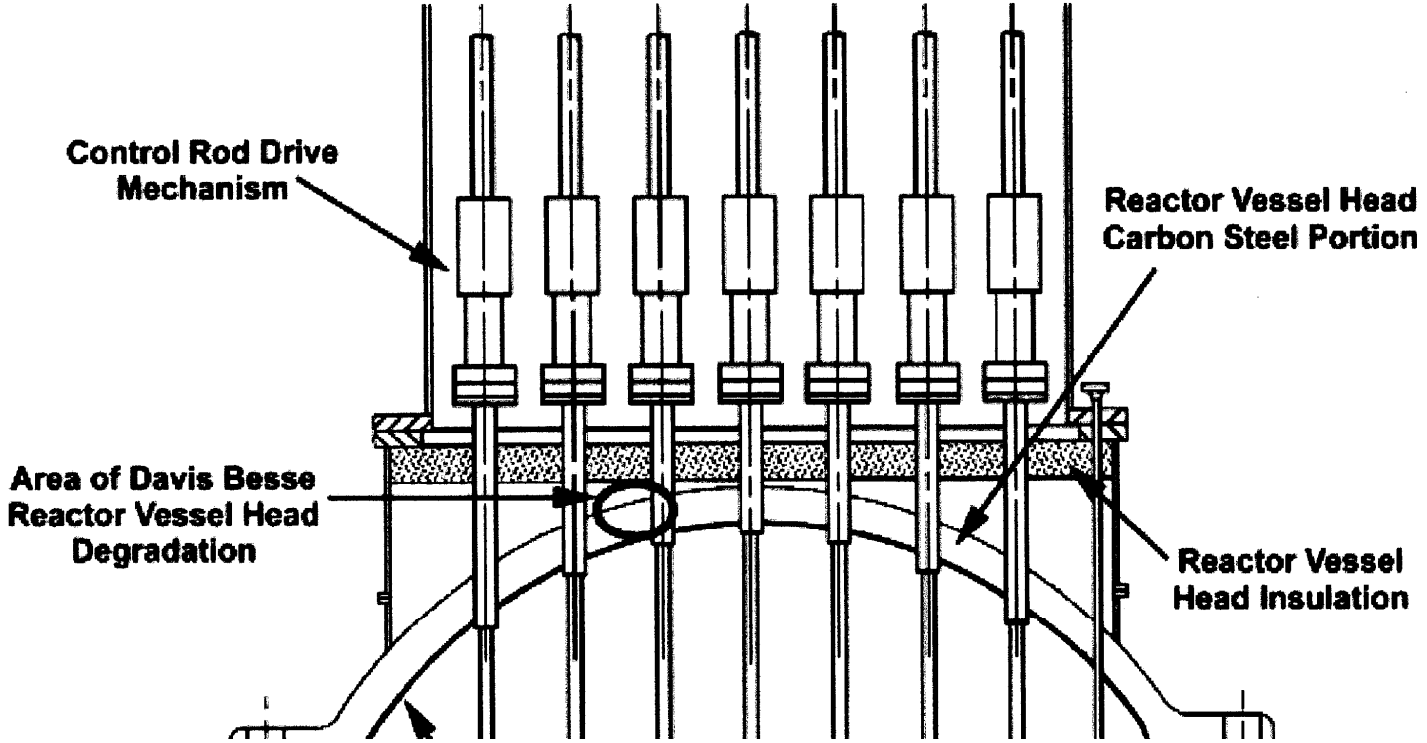


Černobilski eko-paradoks

A Close Call -- Davis-Besse

- PWR, 873 MWe, started up in 1977
- Boric acid clogged containment air cooler in 1999
- Containment radiation monitor showed contamination and clogging in May 1999
- Significant head corrosion began in 1998 or earlier
- Five control rod penetration nozzles were cracked, 3 penetrated nozzle wall
- Large cavity in vessel wall, sealed only by vessel liner
- NRC has placed 27 PWR plants in the ‘high risk’ category for vessel corrosion - some in vessel bottom penetations

Davis-Besse Head Corrosion Location

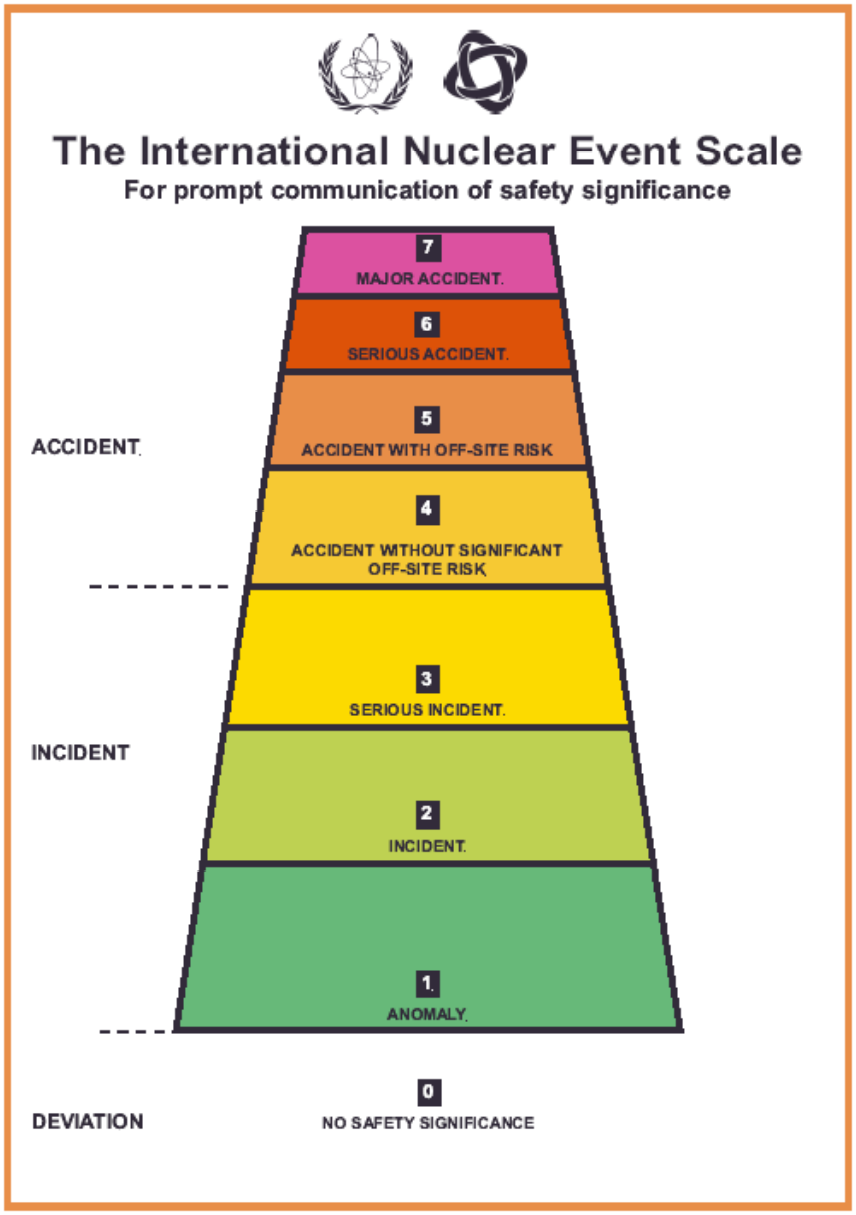


DB - A Hole in the Head

Stainless steel liner bulged, but did not fail

Međunarodna skala nuklearnih događaja

Promptna informacija o značaju događaja za sigurnost



INES

Basic Structure of the Scale

(Criteria given in matrix are broad indicators only)
Detailed definitions are provided in the INES User's Manual

	CRITERIA OR SAFETY ATTRIBUTES		
	OFF-SITE IMPACT	ON-SITE IMPACT	DEFENCE IN DEPTH DEGRADATION
7 MAJOR ACCIDENT	MAJOR RELEASE: WIDESPREAD HEALTH AND ENVIRONMENTAL EFFECTS		
6 SERIOUS ACCIDENT	SIGNIFICANT RELEASE: LIKELY TO REQUIRE FULL IMPLEMENTATION OF PLANNED COUNTERMEASURES		
5 ACCIDENT WITH OFF-SITE RISK	LIMITED RELEASE: LIKELY TO REQUIRE PARTIAL IMPLEMENTATION OF PLANNED COUNTERMEASURES	SEVERE DAMAGE TO REACTOR CORE/RADIOLOGICAL BARRIERS	
4 ACCIDENT WITHOUT SIGNIFICANT OFF-SITE RISK	MINOR RELEASE: PUBLIC EXPOSURE OF THE ORDER OF PRESCRIBED LIMITS	SIGNIFICANT DAMAGE TO REACTOR CORE/RADIOLOGICAL BARRIERS/FATAL EXPOSURE OF A WORKER	

INES

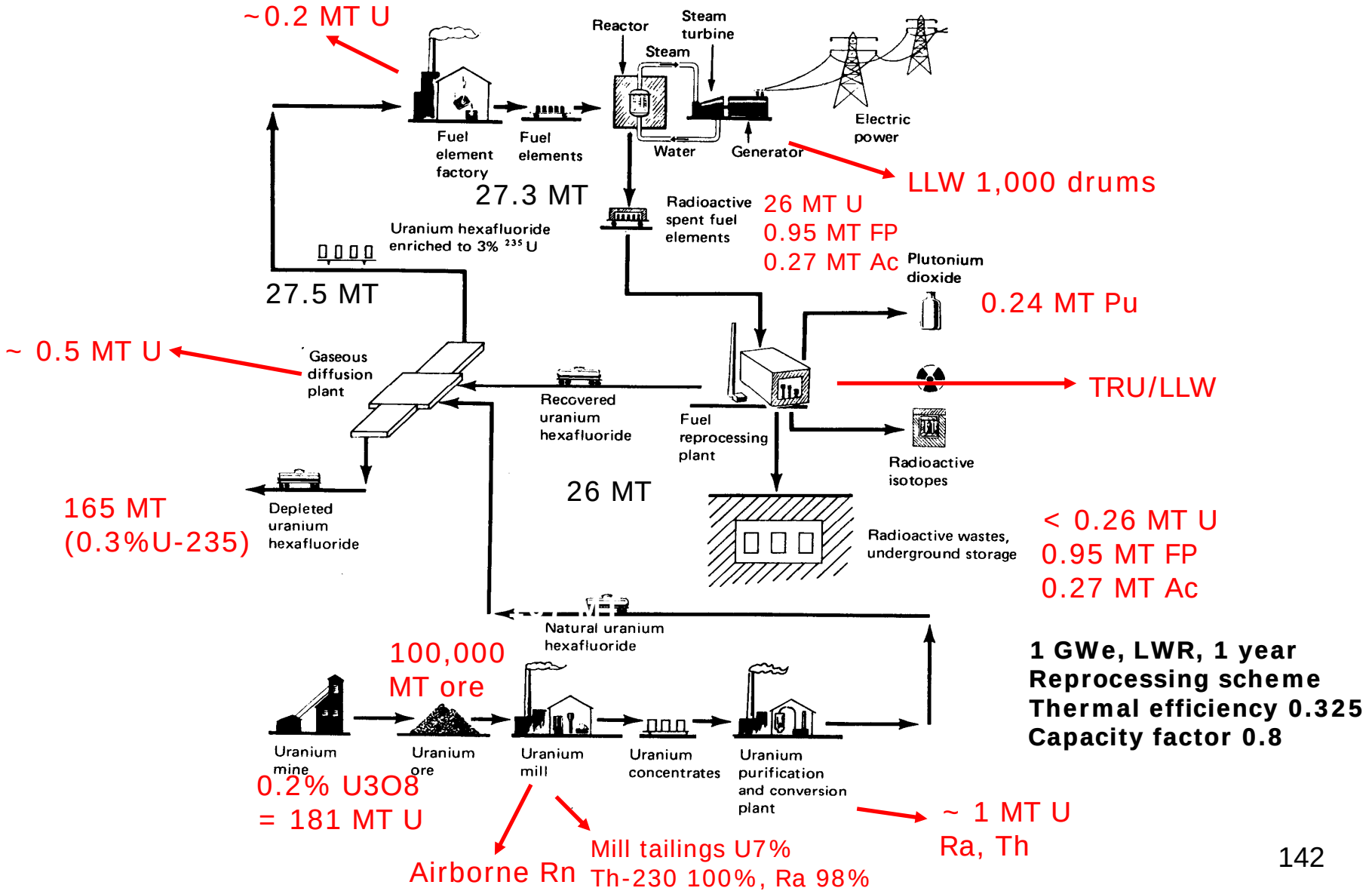
4 ACCIDENT WITHOUT SIGNIFICANT OFF-SITE RISK	MINOR RELEASE: PUBLIC EXPOSURE OF THE ORDER OF PRESCRIBED LIMITS	SIGNIFICANT DAMAGE TO REACTOR CORE/RADIOLOGICAL BARRIERS/FATAL EXPOSURE OF A WORKER	
3 SERIOUS INCIDENT	VERY SMALL RELEASE: PUBLIC EXPOSURE AT A FRACTION OF PRESCRIBED LIMITS	SEVERE SPREAD OF CONTAMINATION/ACUTE HEALTH EFFECTS TO A WORKER	NEAR ACCIDENT NO SAFETY LAYERS REMAINING
2 INCIDENT		SIGNIFICANT SPREAD OF CONTAMINATION/ OVEREXPOSURE OF A WORKER	INCIDENTS WITH SIGNIFICANT FAILURES IN SAFETY PROVISIONS
1 ANOMALY			ANOMALY BEYOND THE AUTHORIZED OPERATING REGIME
0 DEVIATION	**NO**	**SAFETY**	**SIGNIFICANCE**
OUT OF SCALE EVENT	**NO SAFETY RELEVANCE**		

Istrošeno gorivo

Privremeno skladištenje istrošenog goriva

- Skladištenje istrošenog goriva od napuštanja reaktora do konačnog odlaganja
- Mokro (bazen za istrošeno gorivo)
- Suho (posebni spremnici nakon inicijalnog hlađenja)
- Daju vremena za kvalitetan izbor konačnog odlagališta
- Omogućuju preradu istrošenog goriva

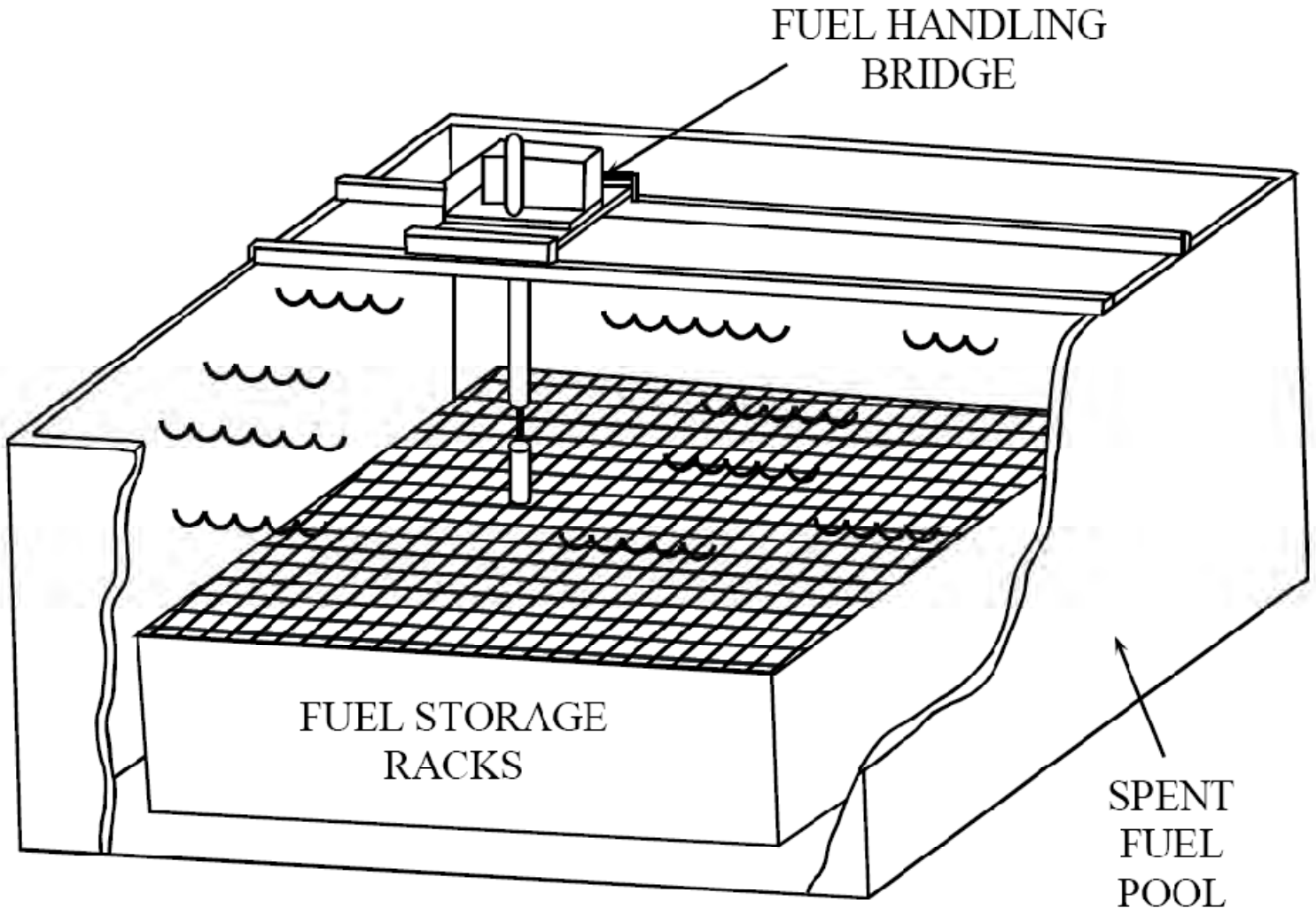
Nuclear Fuel Cycle & Waste Generation



Bazen za istrošeno gorivo

- Trenutno obično primaju istrošeno gorivo proizvedeno za cijeli životni vijek elektrane
- Osiguravaju štit od zračenja i hlađenje
- Nadzor kritičnosti
- Odgovarajuća zgrada mora garantirati mehaničku zaštitu i kontrolirani pristup
- Potrebno aktivno hlađenje

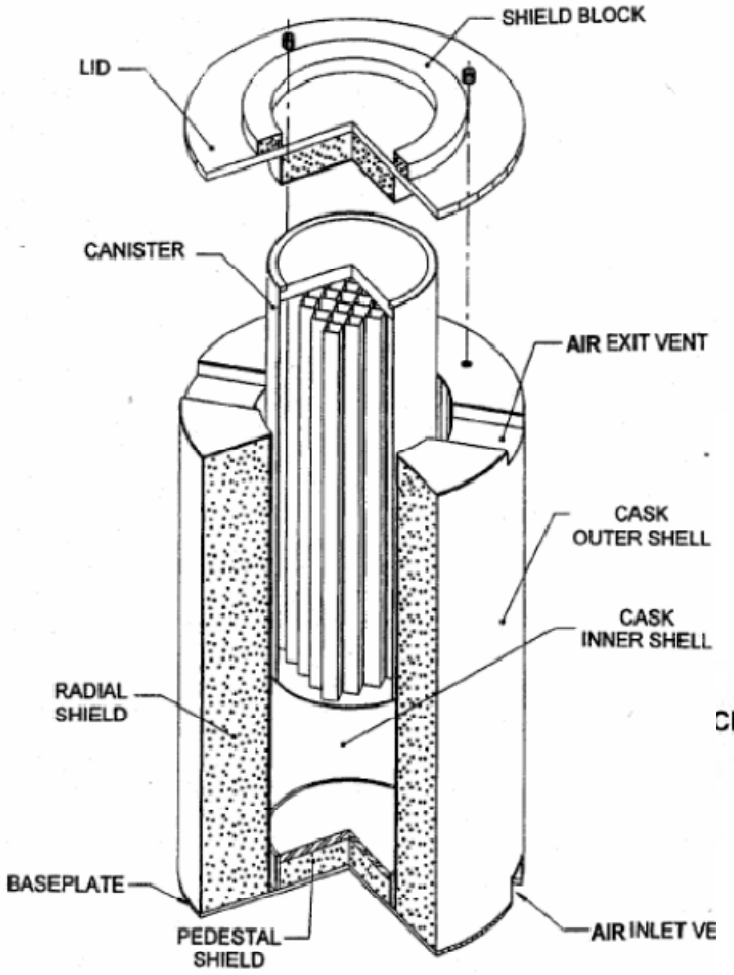
Bazen za istrošeno gorivo



Privremeno suho skladištenje istrošenog goriva

- Lokacija (elektrana, centralno skladištenje)
- Debeli metalni štit čini zračenje neškodljivim za ljudsko zdravlje
- Hermetički zatvoreni
- Otporni na sva prirodna i ljudska djelovanja
- Ekonomično rješenje
- Trajnost oko 100 godina

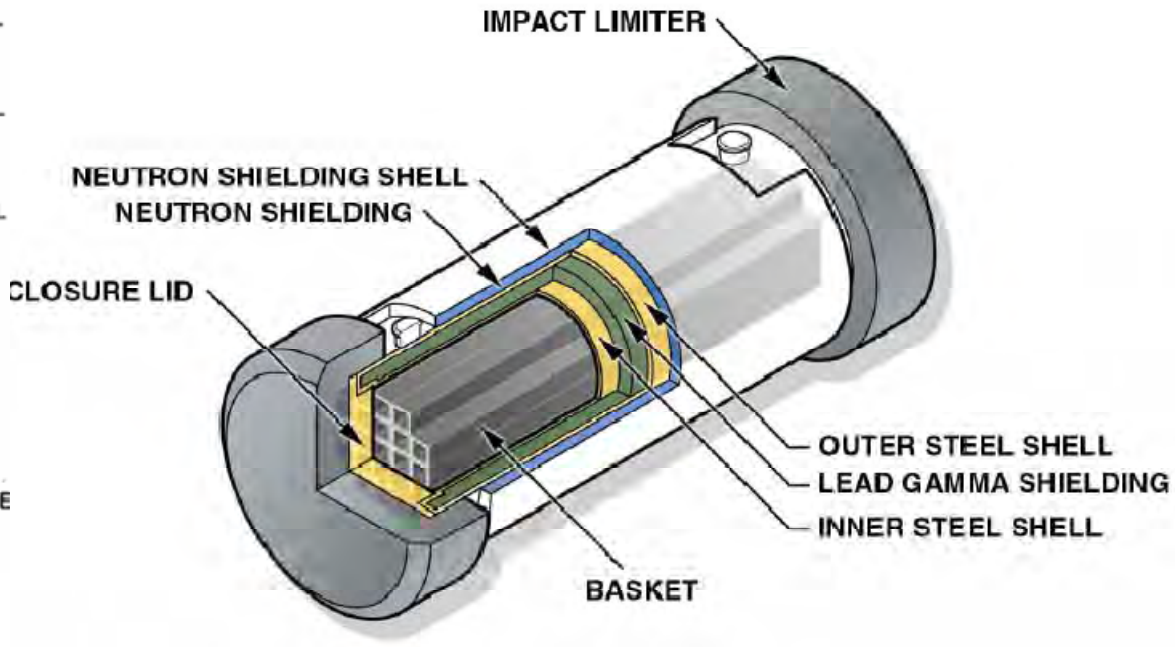
Privremeno suho skladištenje istrošenog goriva



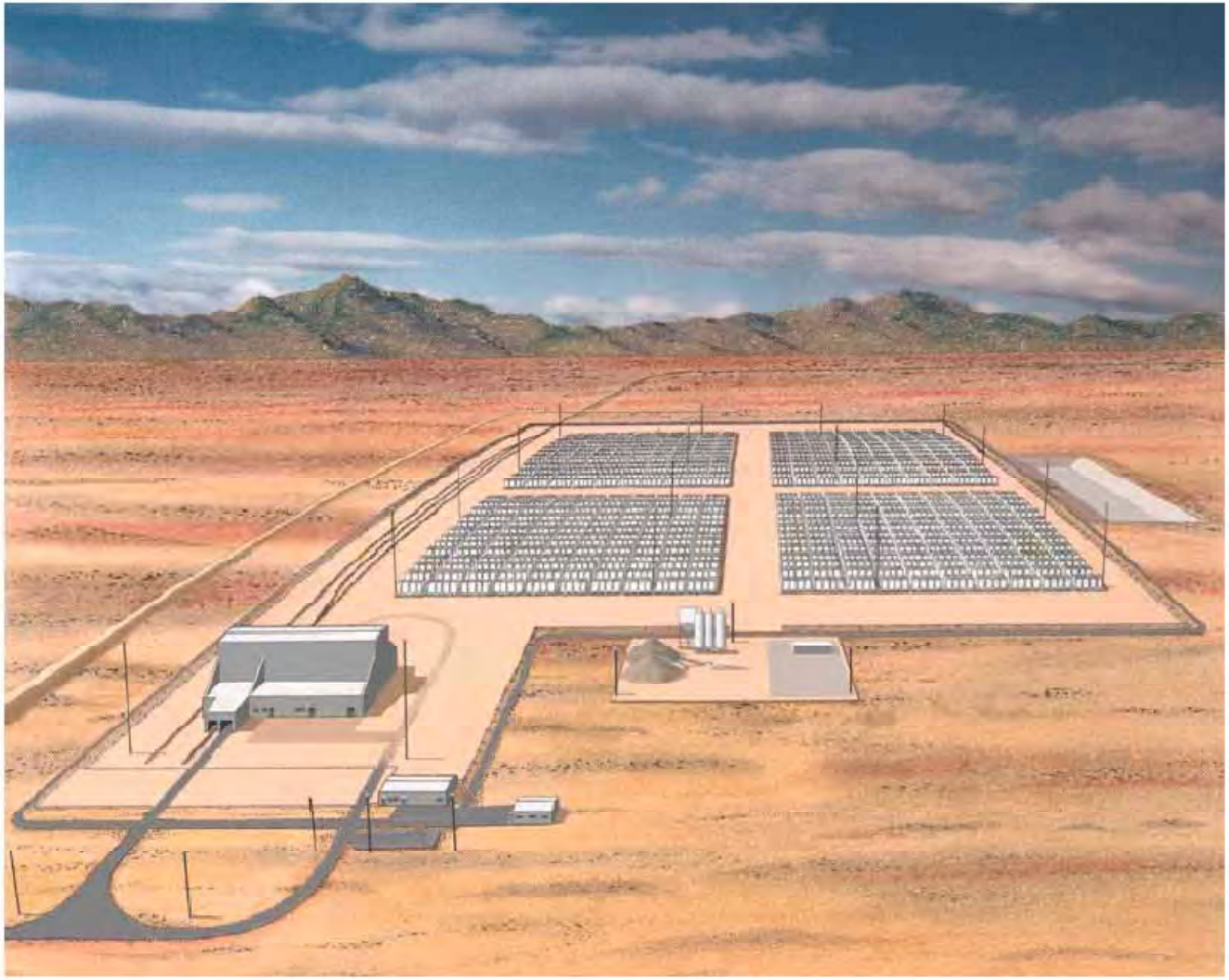
Spremnik za suho skladištenje

Transportni spremnik

Masa oko 200 t



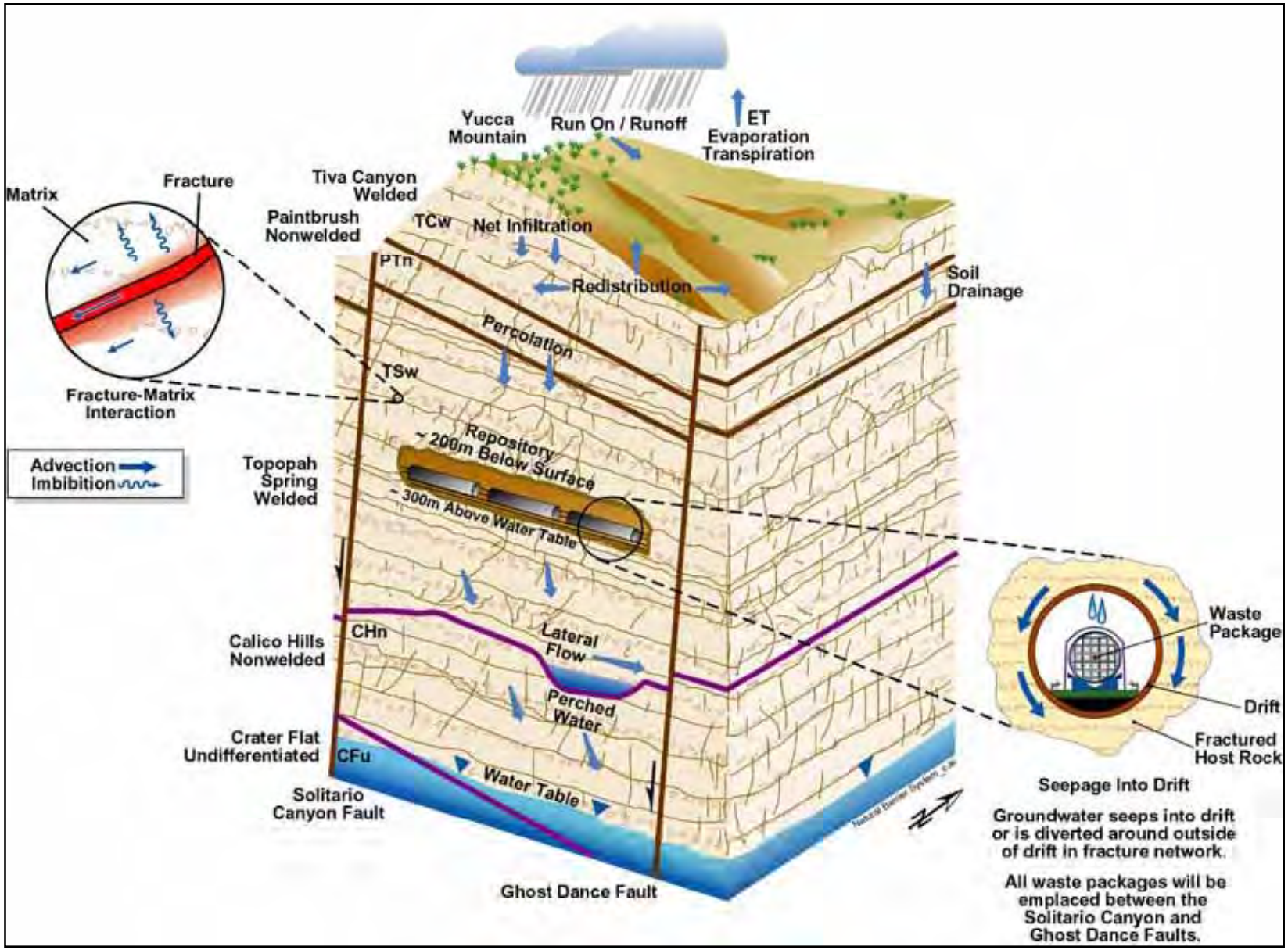
Privremeno suho skladištenje istrošenog goriva



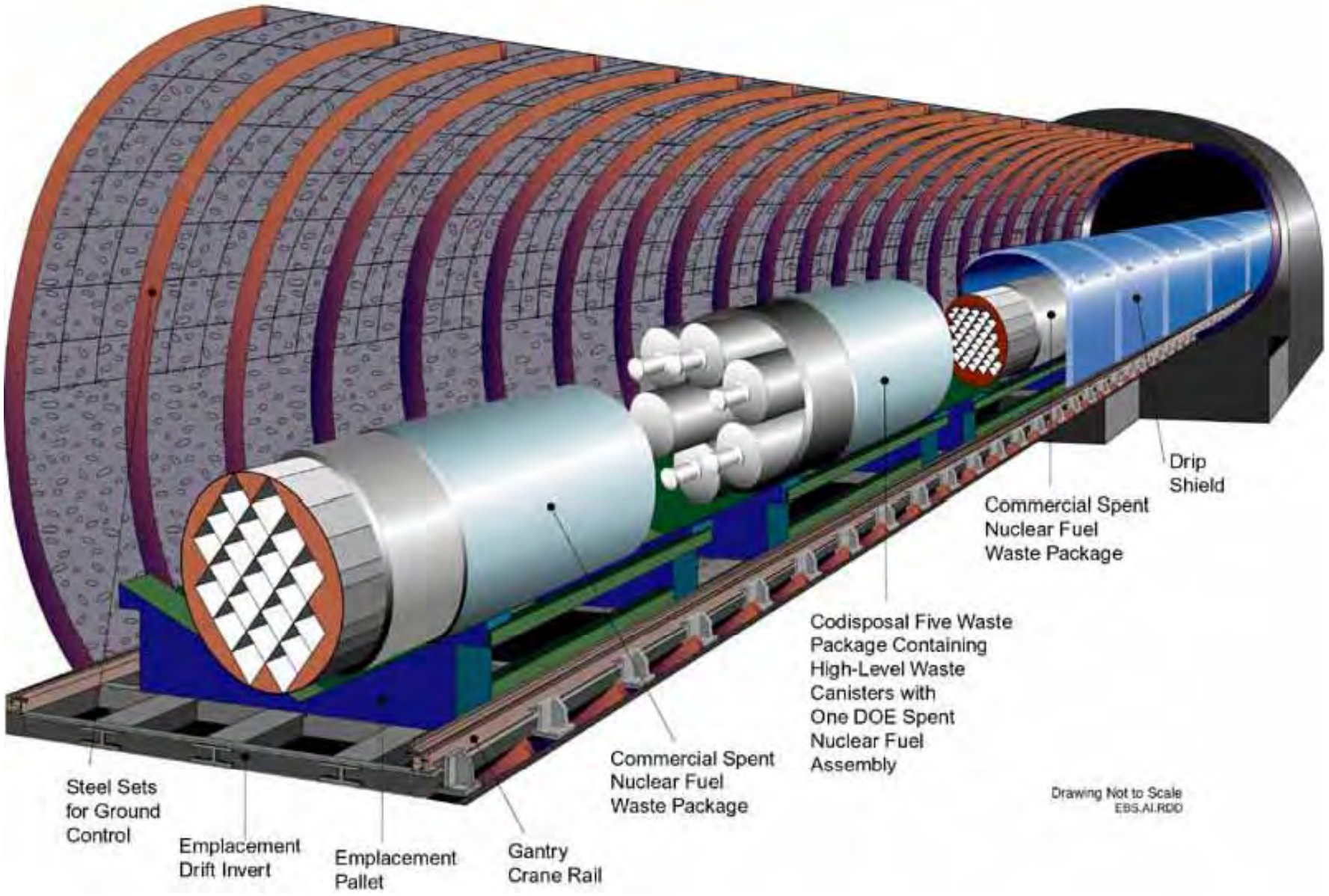
Trajno odlaganje visokoaktivnog otpada

- Spominje se kao najveći problem nuklearne energetike
- Količine su razumne za spremanje
- Direktno zračenje i hlađenje manji problem
- Potrebno onemogućiti ispuštanje radioaktivnosti u ekosustav za dugi niz godina
- Kombinacija prirodnih i inženjerskih barijera
- Tehnički izvedivo ali nema previše uspješnih primjera
- Transmutacija posebno povoljna (količina i trajnost)

Sustav prirodnih barijera za širenje radioaktivnosti

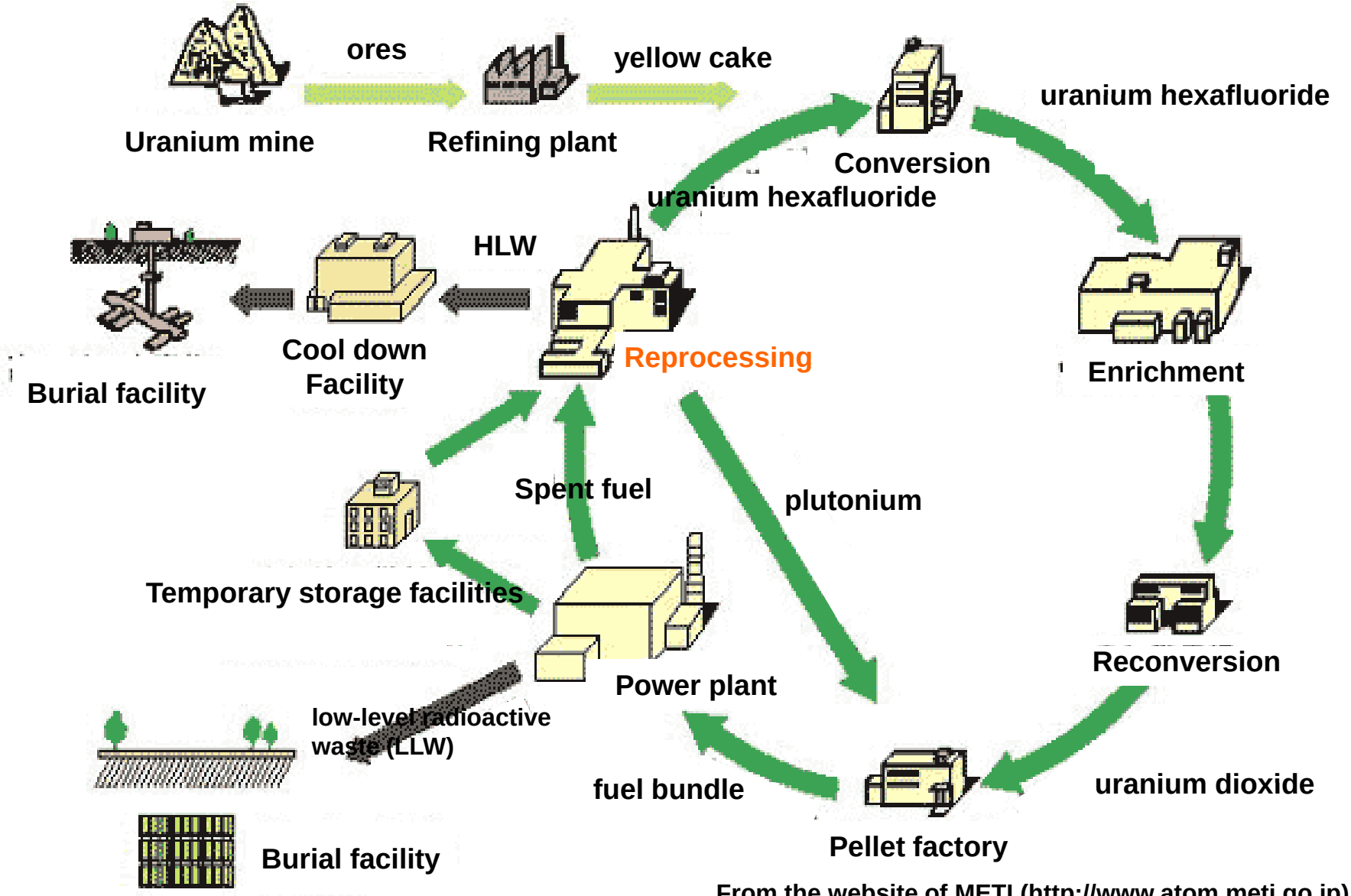


Sustav inženjerskih barijera za širenje radioaktivnosti



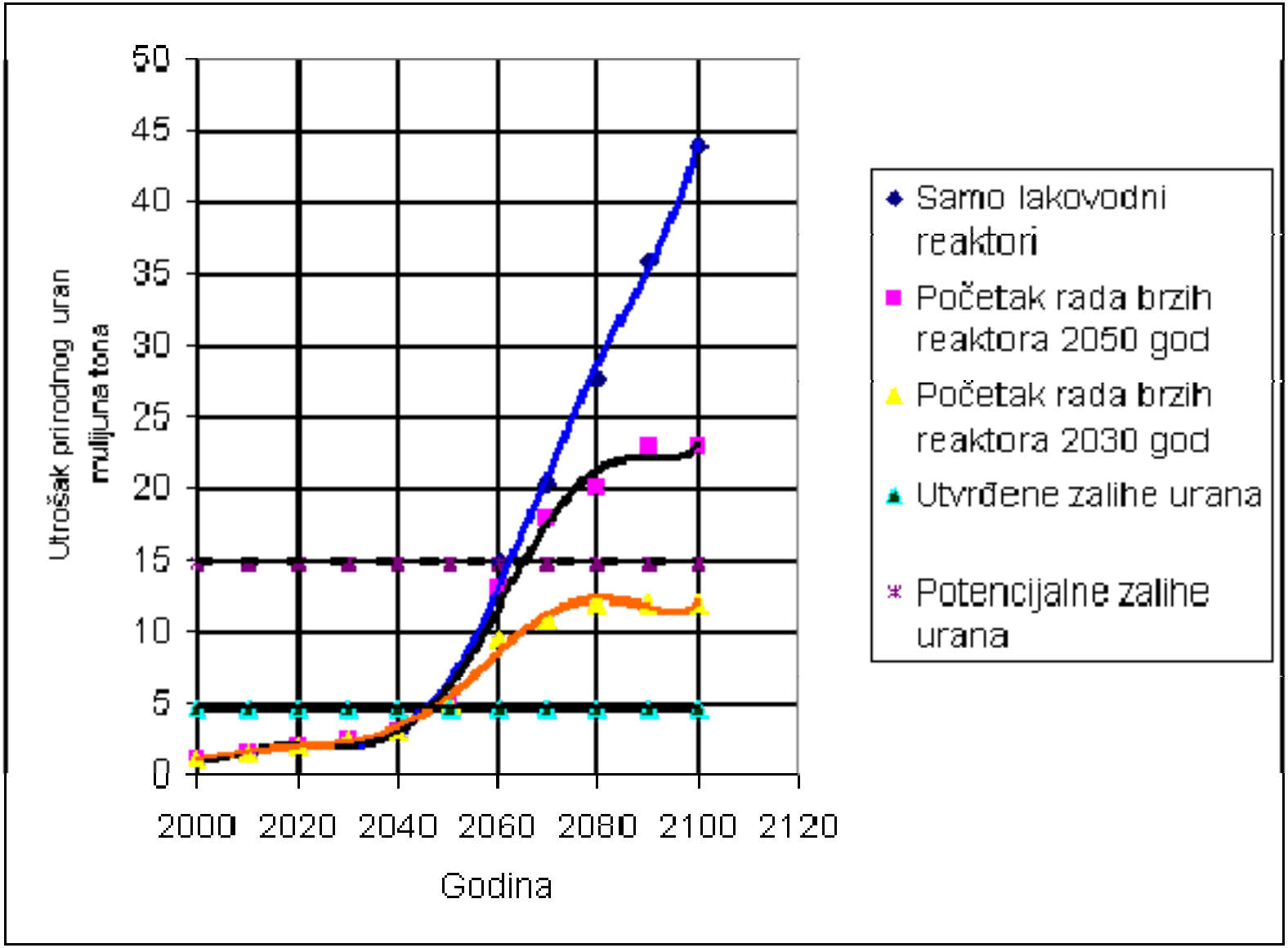
Nuklearni gorivni ciklus

Primjer zatvorenog gorivnog ciklusa

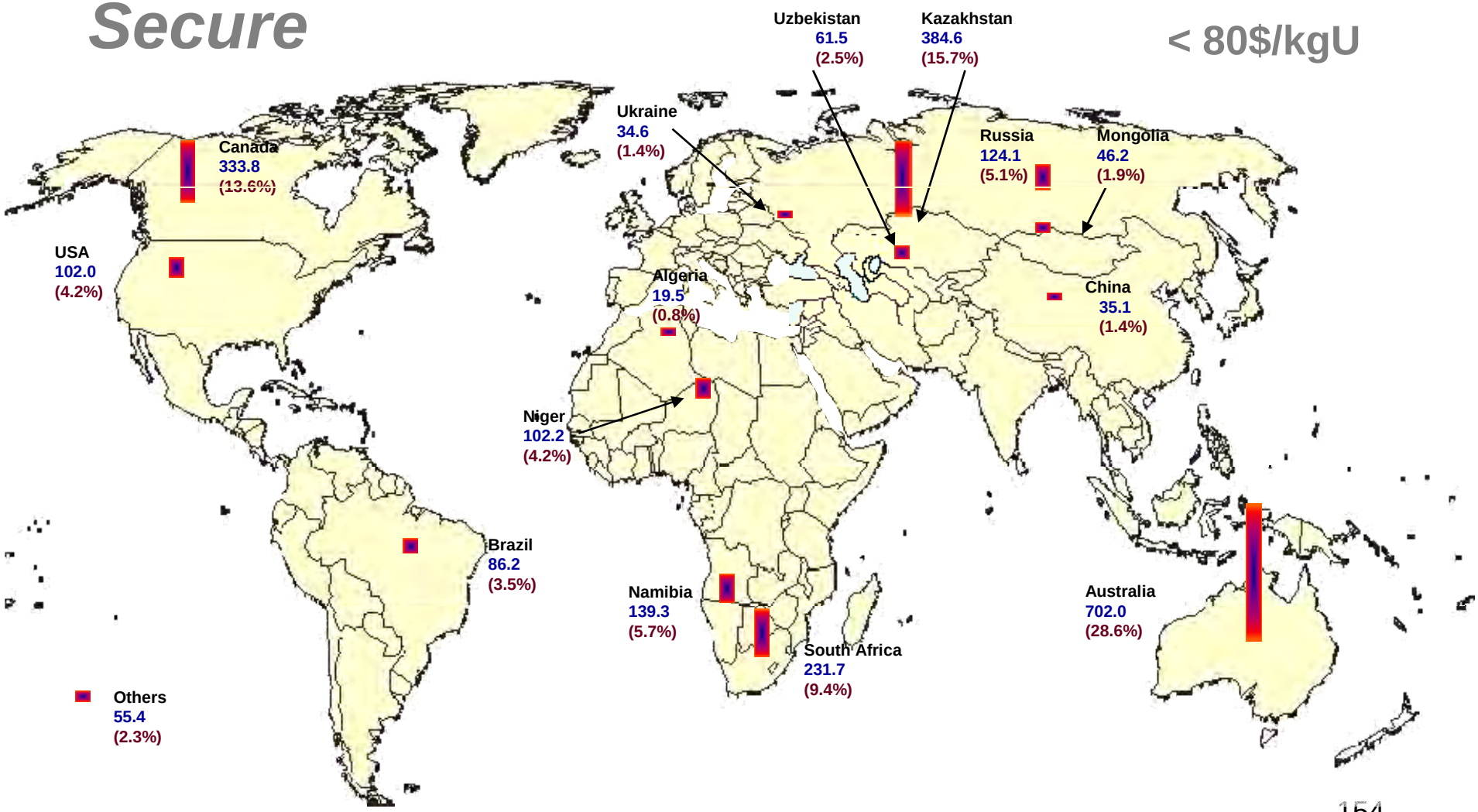


From the website of METI (http://www.atom.meti.go.jp)

Kumulativni potrošak prirodnog urana u ovisnosti o strategiji razvoja nuklearne energetike



Svjetske rezerve urana (stanje početak 2003)



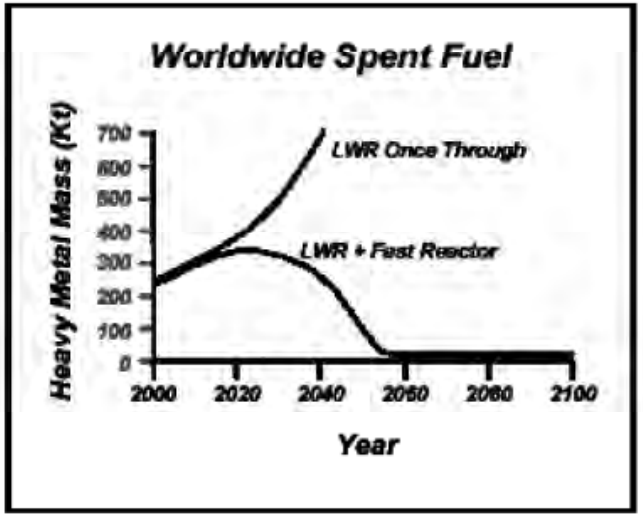
Rezerve urana

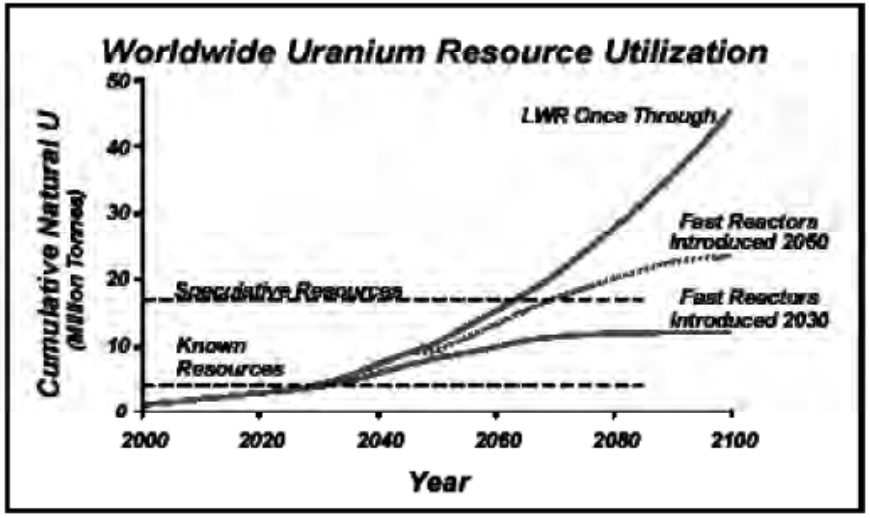
- **Sadašnjost ~ 14.4 MT**
  - **Sigurne rezerve** **3.2 MT**
  - **Procijenjene dodatne I** **1.4 MT**
  - **Procijenjene dodatne II** **2.3 MT**
  - **Spekulativne rezerve** **7.5 MT**

  Potrošnja *~ 0.06 - 0.07 MT/y*
- **Budućnost**
  - **Konvencionalne rezerve ~ 200 god**
  - **Nekonvencionalne rezerve**
    - **Fosfati** **~ 22 MT**
    - **Morska voda** **~ 4000 MT**
  - **Oplodne tehnologije mogu povećati iskoristivost goriva 50 do 70 puta (zatvoreni ciklusi)**

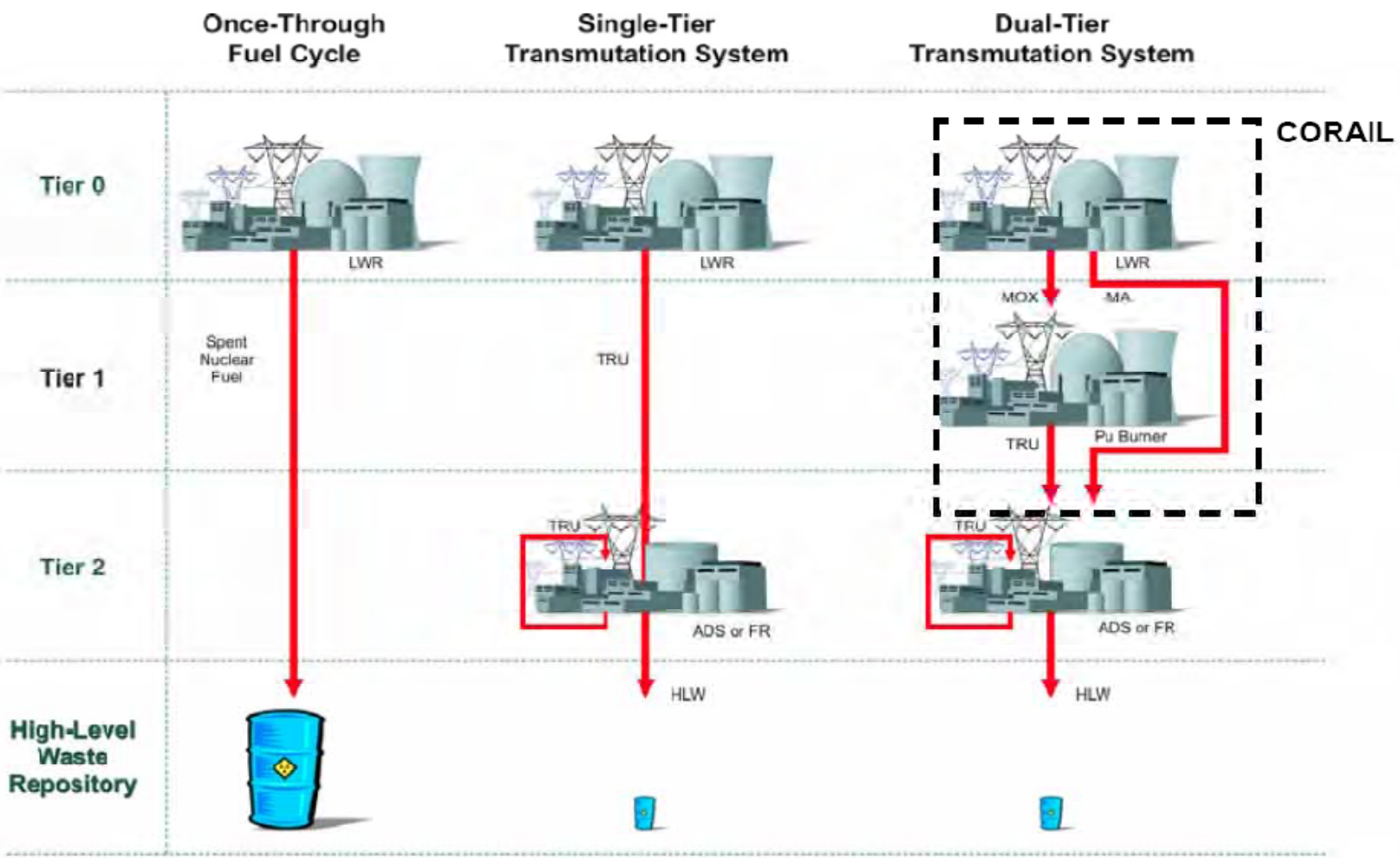
Concept Description

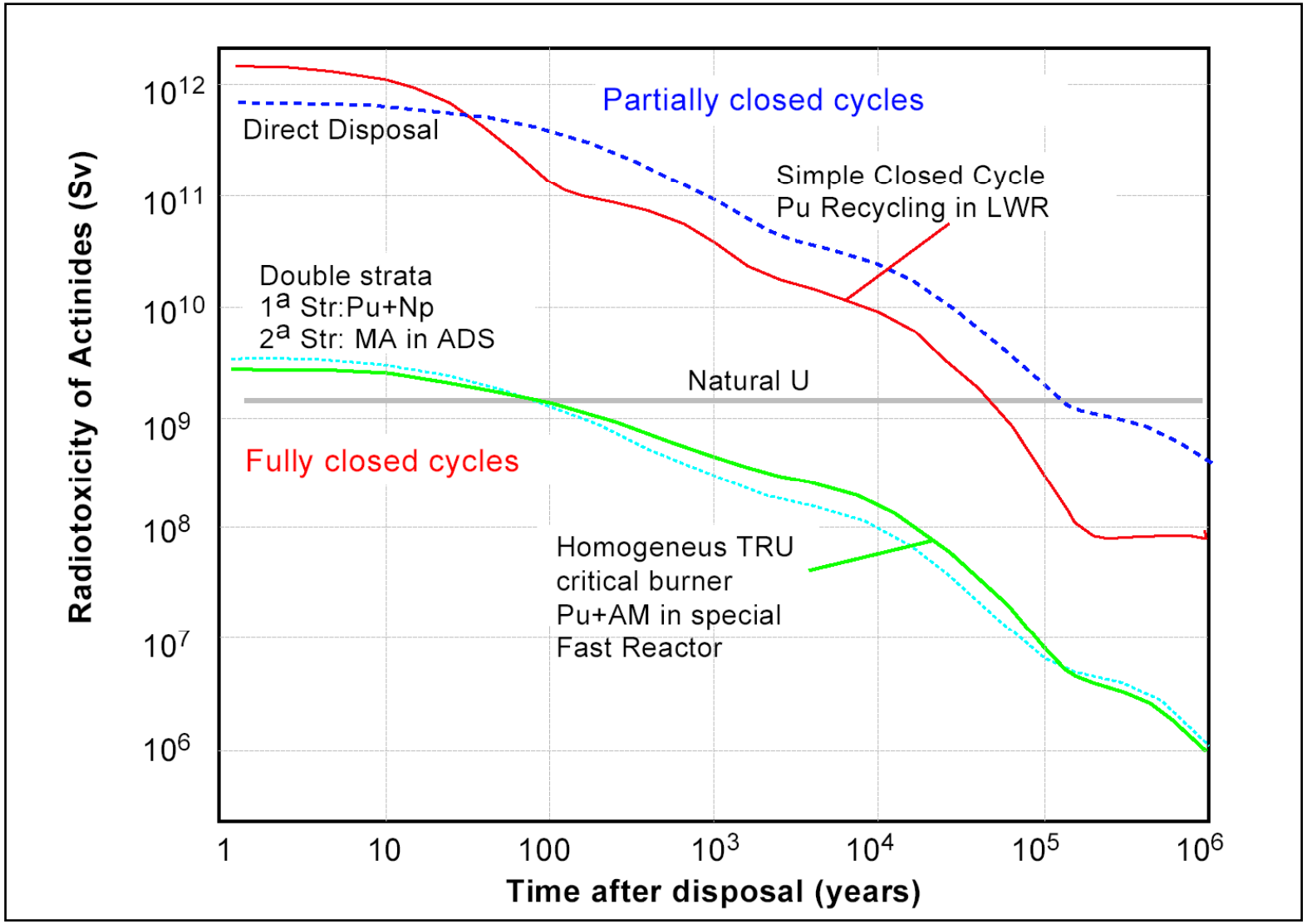
- *Sodium-cooled fast spectrum reactors using a closed fuel cycle with full actinide recycle*
- *Missions: Actinide management and electricity production*
  - » *Reduces physical demands on repositories*
  - » *Utilizes the entire natural resource of fissionable material*
- *Estimated Deployment Date: 2020*





Transmutation System Approach




Radiotoxicity of Actinides (Sv)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
Partially closed cycles
Direct Disposal
Simple Closed Cycle
Pu Recycling in LWR
Double strata
1a Str:Pu+Np
2a Str: MA in ADS
Natural U
Fully closed cycles
Homogeneus TRU
critical burner
Pu+AM in special
Fast Reactor
1
10
100
10^3
10^4
10^5
10^6
Time after disposal (years)

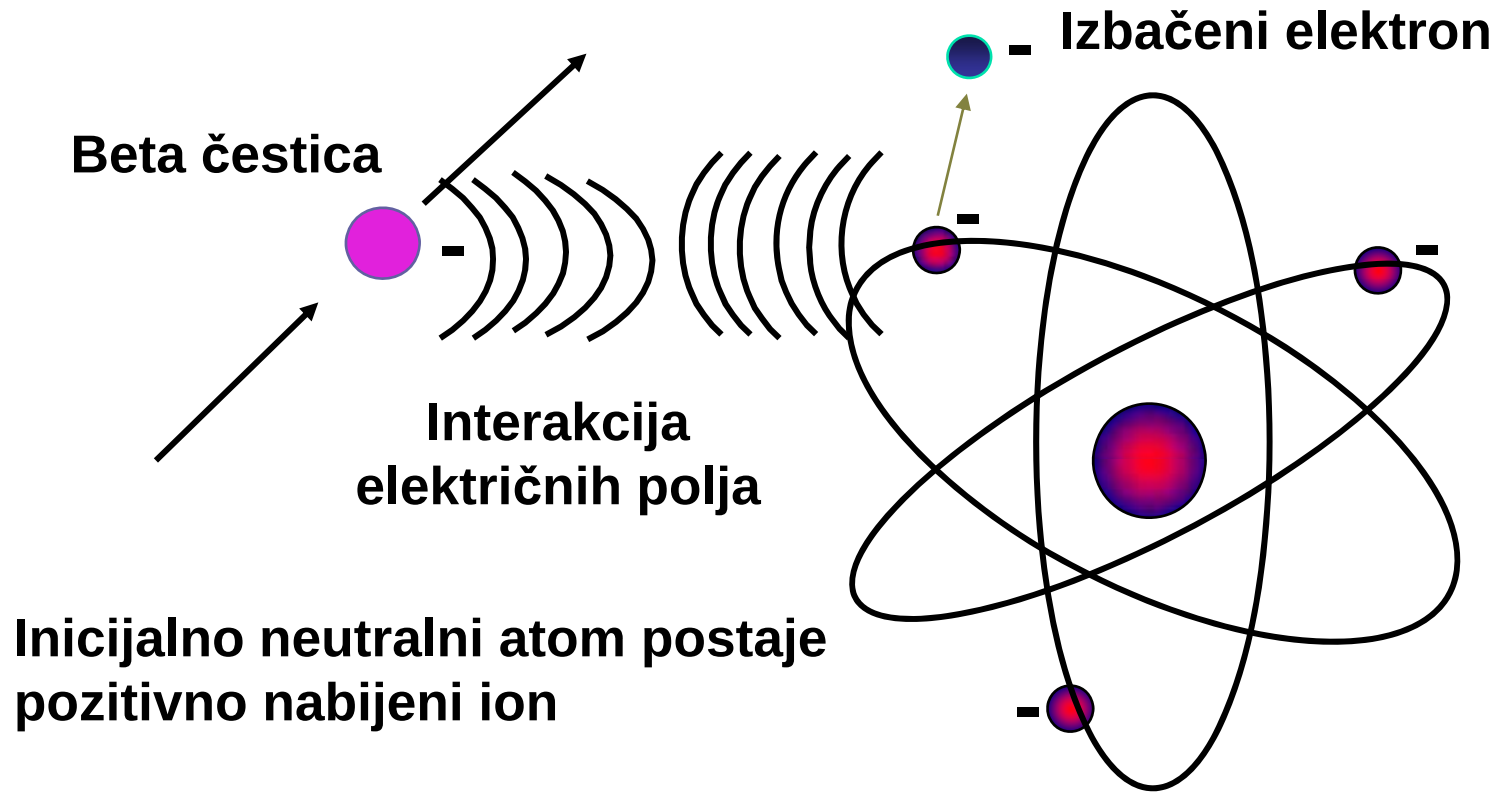
Zračenje

Zašto je zračenje štetno?

- Zračenje je energija u obliku čestica ili valova
- Može biti ionizirajuće i neionizirajuće
- Zračenje deponira male količine energije u materijalu:
  - Ionizira i mijenja atome
  - Oštećenje ćelija i DNK izaziva mutacije i rak
  - Slični efekti su posljedica izlaganja nekim kemikalijama
  - Većina oštećenja je izazvana produkcijom iona

Ionizacija

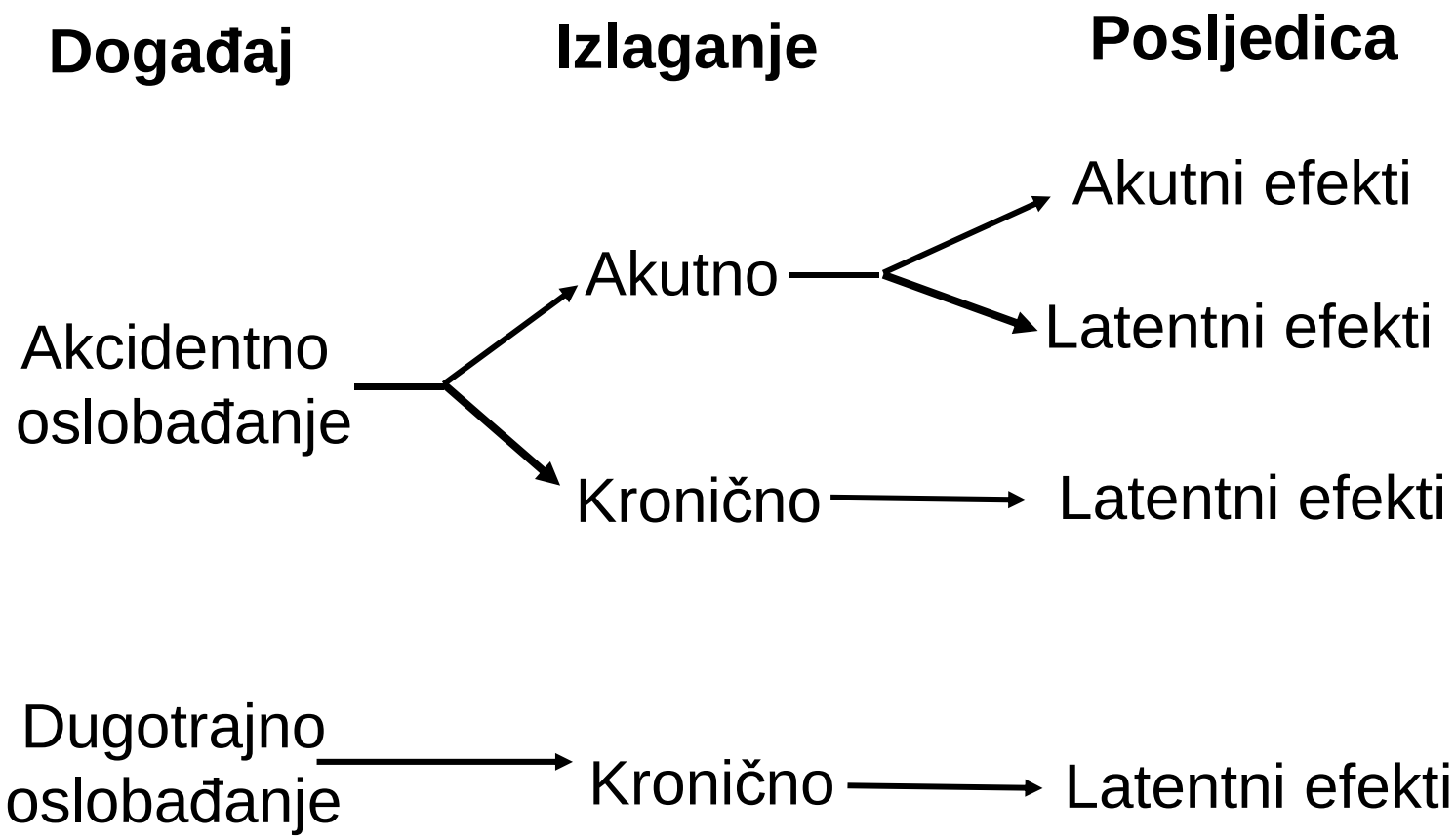
Formiranje nabijenog atoma



Zaštita od zračenja

- Može biti jednostavna i složena
- Vanjski i unutarnji izvor
- Osnovni principi:
  - Ograniči izloženost (vrijeme)
  - Povećaj udaljenost od izvora zračenja
  - Upotrijebi štit od zračenja
- Jednostavna zaštita za vanjsku izloženost
- Za izvor: smanjiti volumen, imobilizirati, oklopiti

Rizik i posljedice



Izlaganje zračenju

- Akutno – velike doze primljene unutar kreće g vremena
  - Akutni radijacijski sindrom
- Kronično – manje doze primljene unutar dužeg vremena (ćelije imaju vremena za oporavak)
  - Povećani rizik za rak (+0.07% po primljenom remu tijekom životnog vijeka, referentni rizik od raka 25%)
  - Genetski defekti
- Veza doza-efekt za akutne doze jasna
- Za male doze postoji više hipoteza

Primljena doza i moguća posljedica

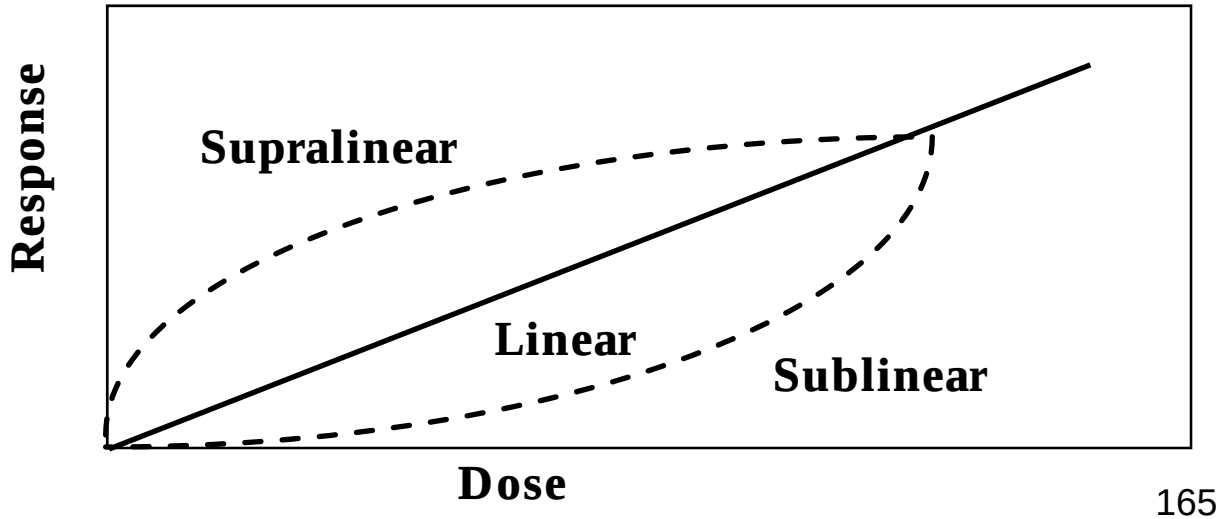
- Modeli se razlikuju po tome kako uzimaju u obzir rizik od malih doza

$$R(d) = \text{const} \times d^m$$

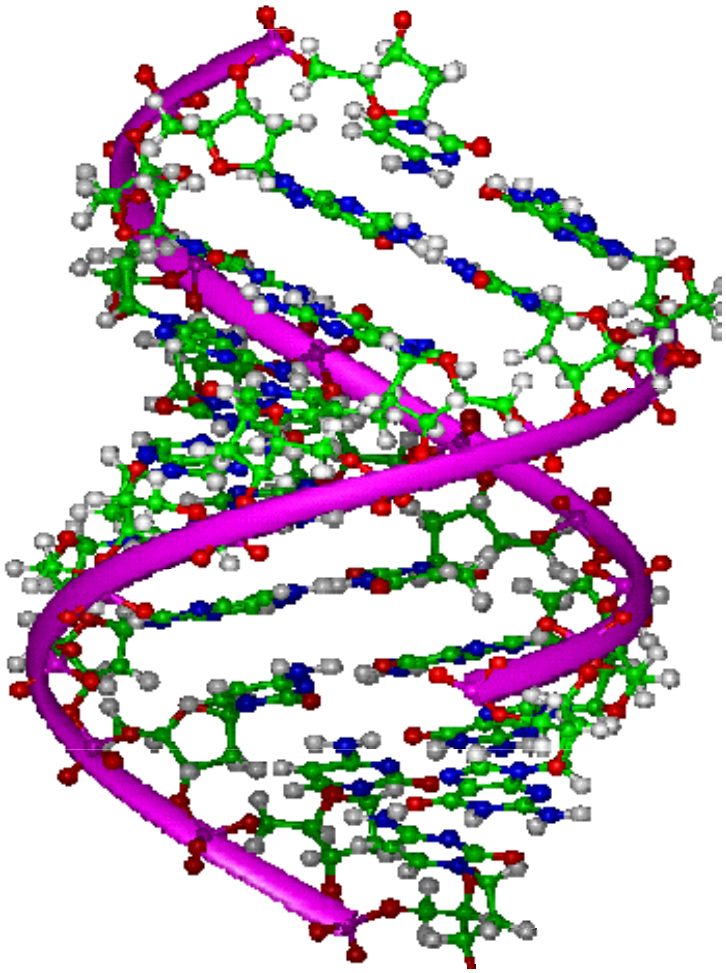
m =1 linear

m>1 sublinear

m<1 supralinear



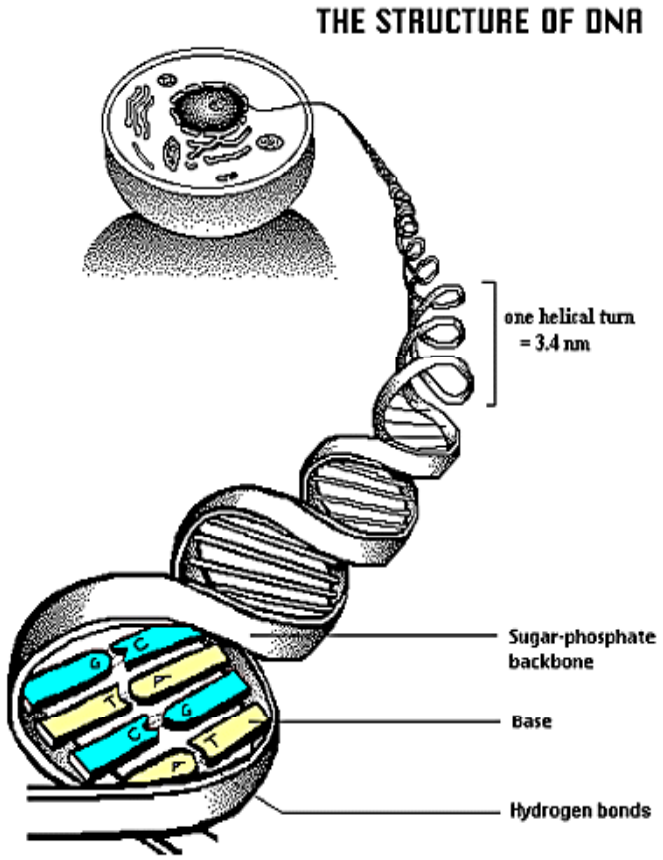
DNK i zračenje



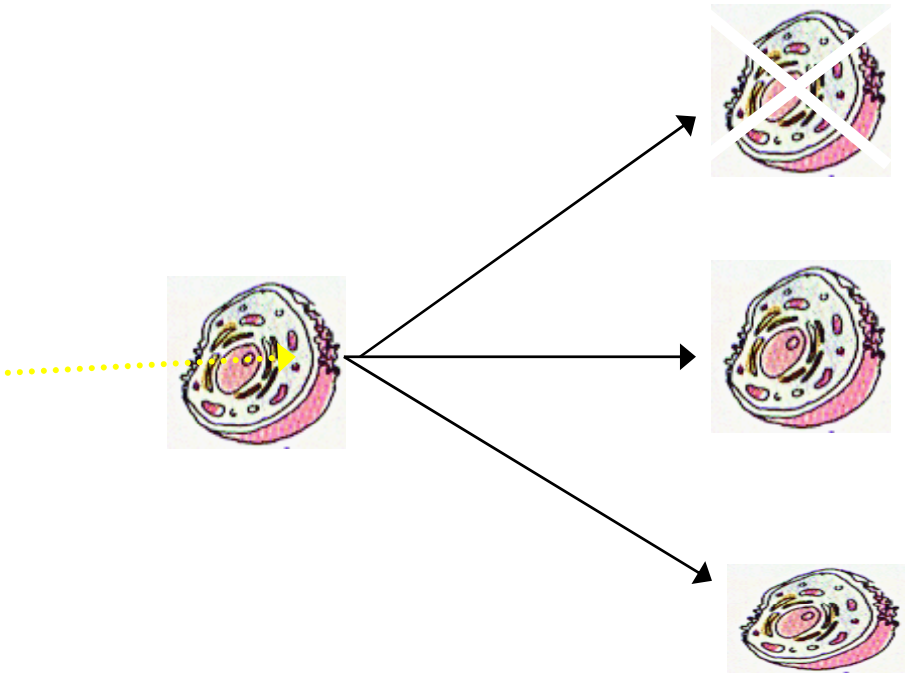
Ionizirajuće zračenje na ćelijskom nivou

- Uzrokuje prekide u jednom ili oba DNK lanca;

- Uzrokuje formiranje slobodnih radikala



Utjecaj na ćeliju



Smrt ćelije

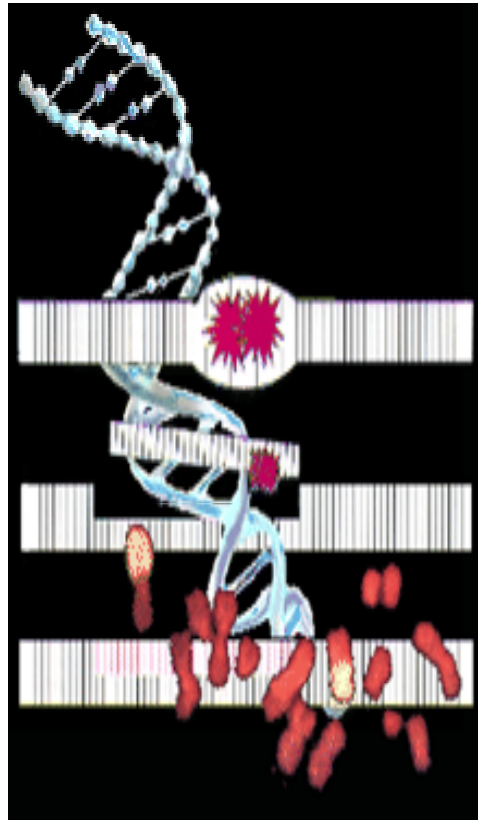
Popravak ćelije

Promjena ćelije

Da li je promjena dobra ili loša?

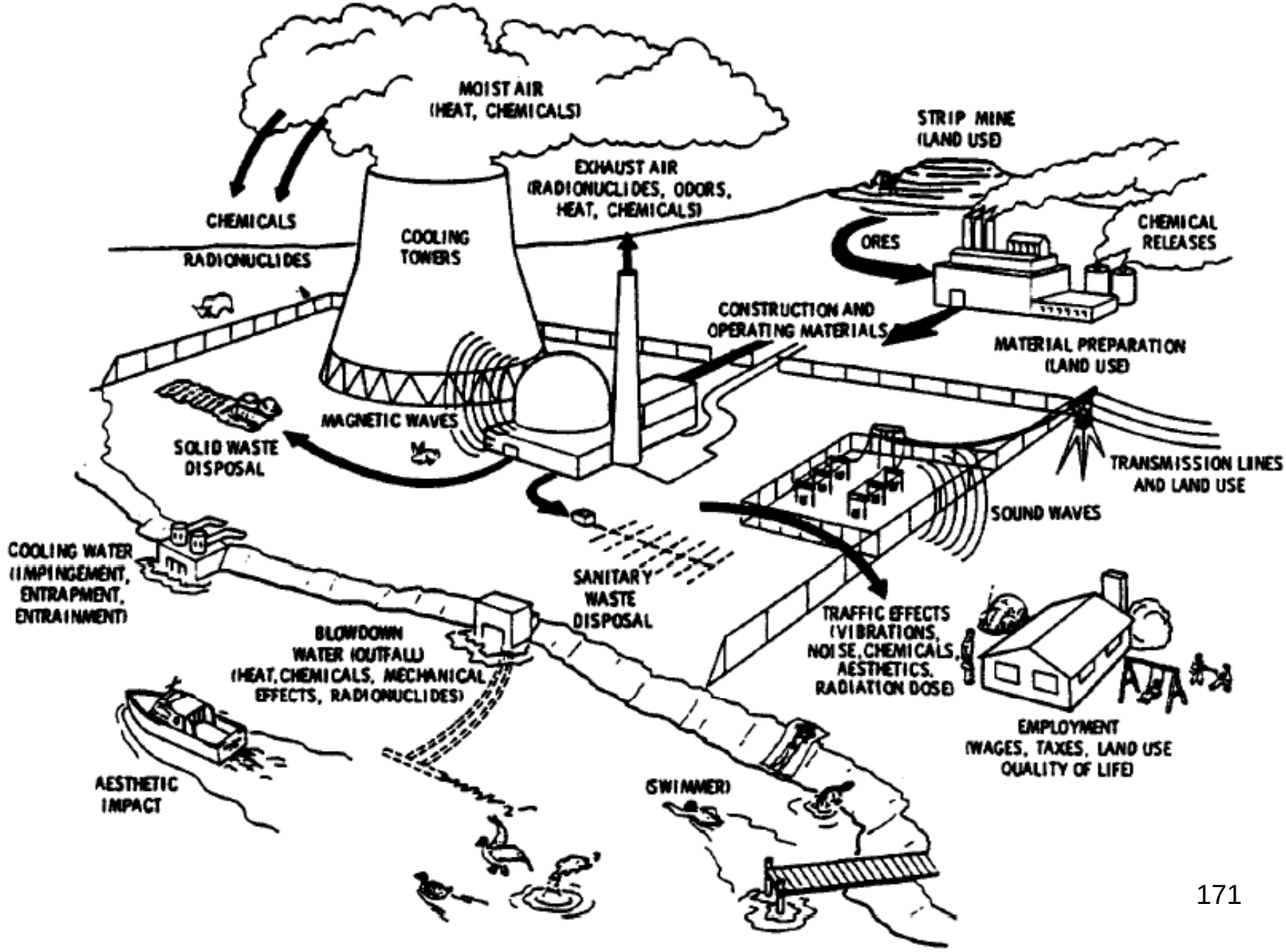
Tijelo posjeduje mehanizme zaštite

- **DNK oštećenje može dovesti do disfunkcije ćelije ili smrti.**
- **U tijelu ima oko 60 10^{12} ćelija**
  - **Smatra se da svaka ćelija biva pogođena na neki način svakih 10 s, milioni DNK prekida po ćeliji svake godine.**
  - **Pozadinsko zračenje izaziva 5 do 10 DNK prekida po ćeliji svake godine.**
- **Tijelo posjeduje efikasne mehanizme popravke oštećenja DNK**
- **Ćelije koje se često dijele su osjetljivije na zračenje**



Nuklearna elektrana i okoliš

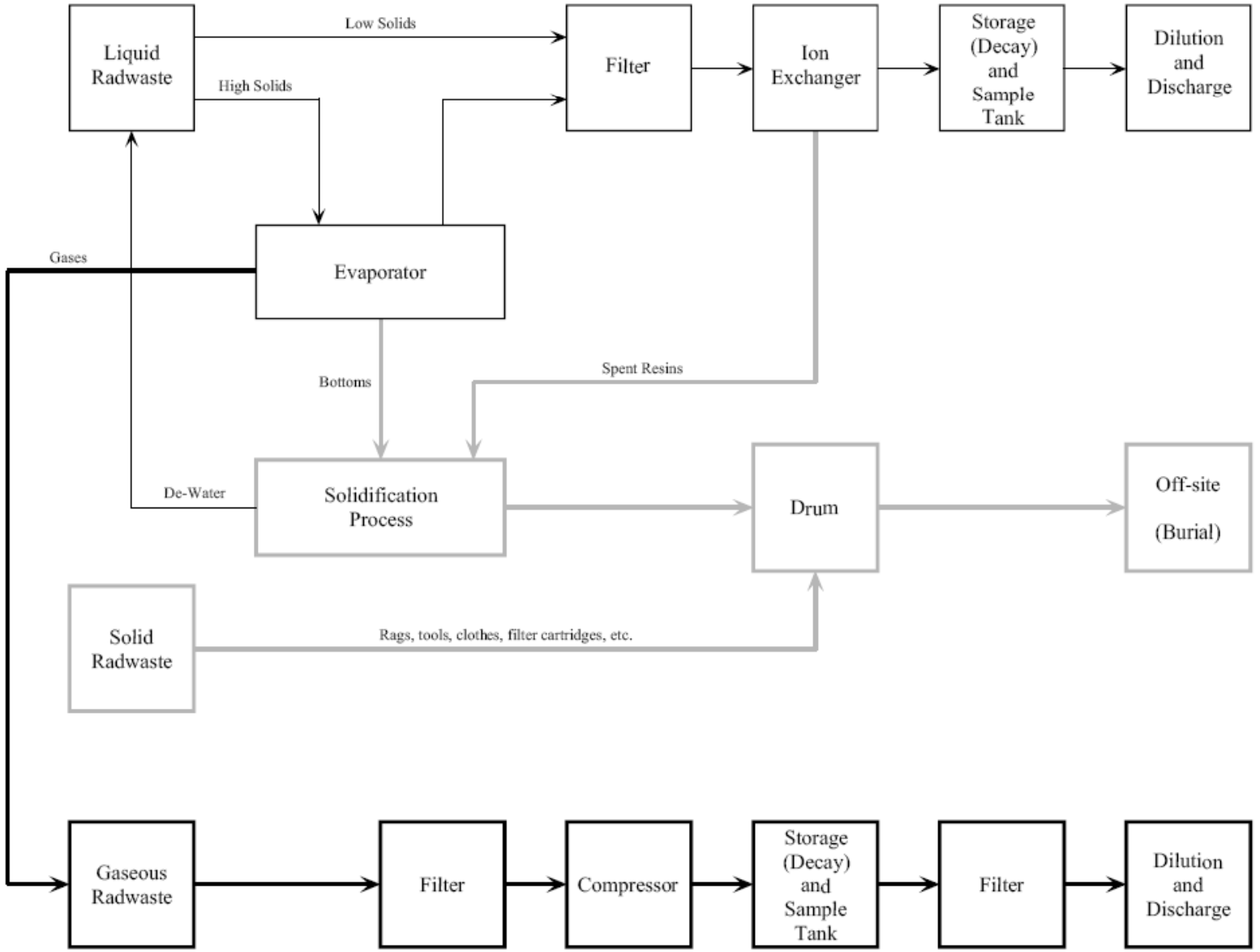
Interakcija NE i okoliša



Normalna ispuštanja

- Vrlo ograničena za vrijeme normalnog pogona
- Pod striktnom administrativnom kontrolom
- Doprinos komparabilan prirodnom nivou zračenja
- Tekuća i plinovita ispuštanja
- Rezultat su curenja goriva i neutronske aktivacije
- “Čekaj i razrijedi” pristup
- ALARA princip

Sustav za tretiranje nisko i srednjeaktivnog otpada



Doze i okoliš

	Tipične	**Interval**
	µSv/god	µSv/god
Prirodnog porijekla:		
Tlo + kuća: radon	200	200-100,000
Tlo + kuća: gamma	600	100-1000
Kozmičko (nivo mora)	300	
+20 za svakih 100m elevacije	.....	0-500
Hrana, piće & tkivo	400	100-1000
Ukupno	**1500** (plus dio ovisan o elevaciji)	

Ljudsko djelovanje:

Nuklearni pokusi	3	
Medicina (X-zrake, CT, ... prosjek)	370	do 75,000
Od nuklearne energetike	0.3	
Izgaranje ugljena	0.1	
Kućanski aparati	0.4	
Ukupno	**375**	

Vezano za aktivnosti:

Skijanje	8 po tjednu	
Putovanje avionom	1.5 - 5 po satu	do 5000/god

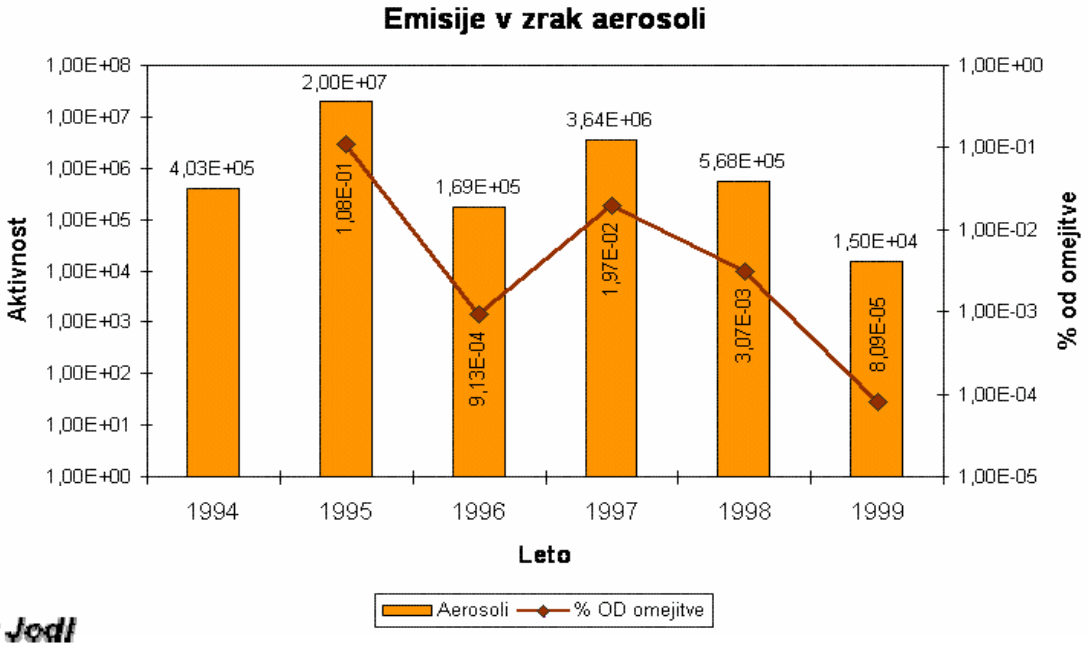
Propisani limiti

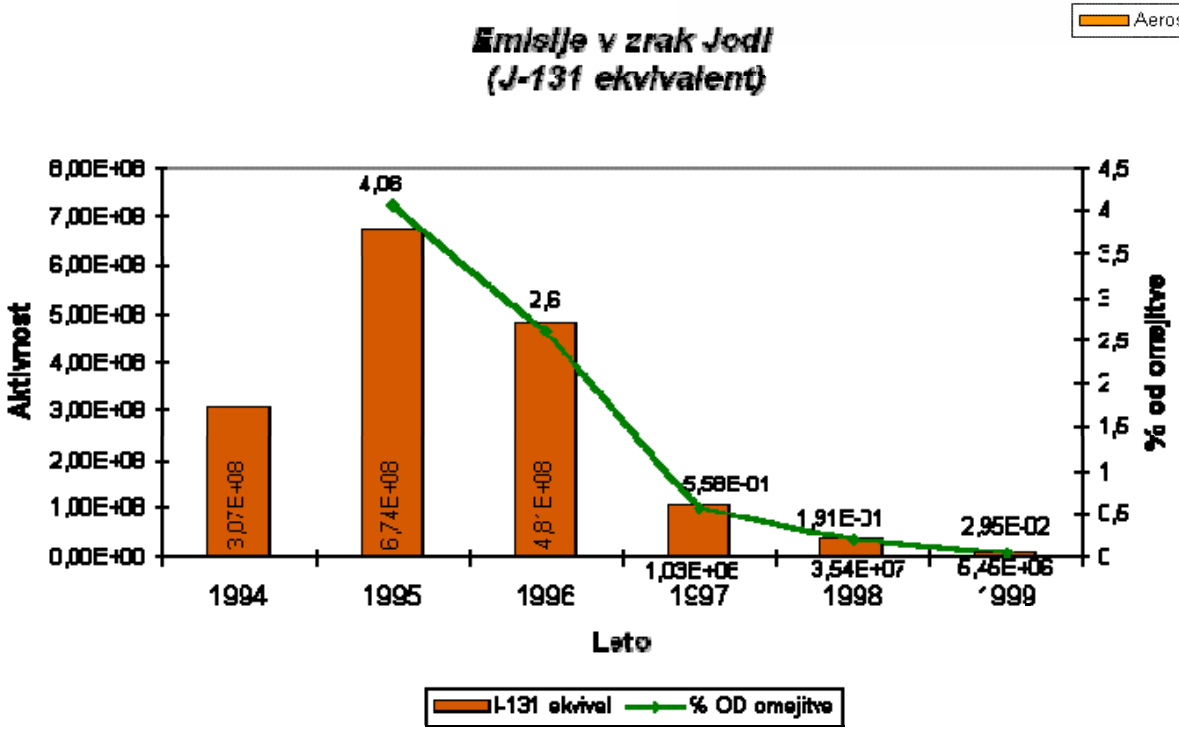
- *ICRP (International Commission for Radiological Protection) preporučava dodatno na pozadinsko zračenje slijedeće limite:*
  ** za stanovništvo 1 mSv/god*
  ** za profesionalce 20 mSv/god*
  (usrednjeno unutar 5 godina)
- *Stvarna ispuštanja u okolici NE su obično u području 0.001 do 0.01 mSv/god*

Plinovita ispuštanja (inventar jezgre)

		Aktivnost (Ci/god)		
Nuklid	Vrijeme poluraspad	30 min	1 dan	60 dan
Kr*-83	1.86 sat	90,000	12	0
Kr-85	10.8 god	250	250	250
Kr*-85	4.4 sat	160,000	3900	0
Kr-87	2.8 sat	510,000	1500	0
Xe*-131	11.9 dan	420	150	10
Xe-133	5.3 dan	160,000	22,000	50
Xe*-133	2.3 dan	6000	50	0
Xe-135	9.2 sat	540,000	0	0
Xe-138	14 min	780,000	0	0

I-131 i aerosoli



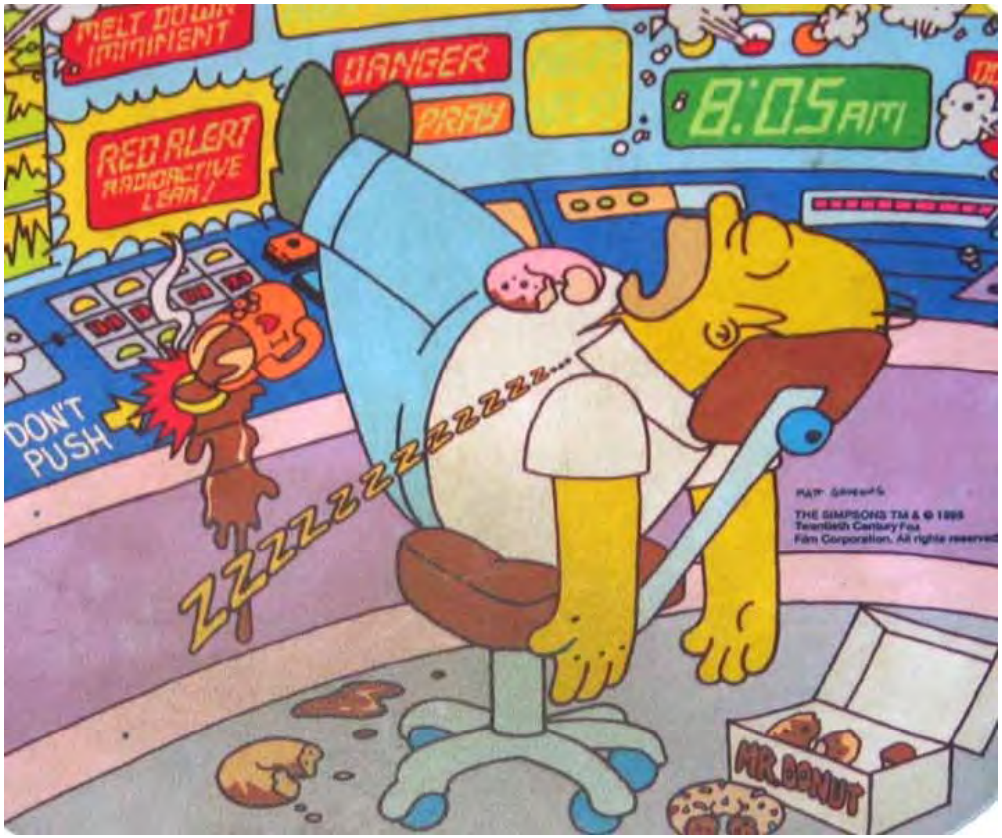


Okoliš i NE

- James Lovelock (“Gaia”), British chemist - 1997 Blue Planet Prize: "We are headed toward a warmer Earth where most life on the planet will have to move to the Arctic basin, to a few islands, ... My justification for nuclear power is that even the results of an all-out nuclear war pale into insignificance compared to what is going to happen.“

- Patrick Moore, a founding member of Greenpeace: "In the 1970s, I equated nuclear energy to holocaust. Now, my views have changed. Nuclear energy may be the energy source that can save our planet from another possible disaster - catastrophic climate change. ... Wind and solar can't replace coal, nuclear, and hydro. Natural gas is too expensive. Nuclear is, by elimination, the only viable substitute for coal. It is that simple.“

Reality Exists!



- Nuklearne elektrane jesu sigurne
- Pobrinimo se da tako i ostane

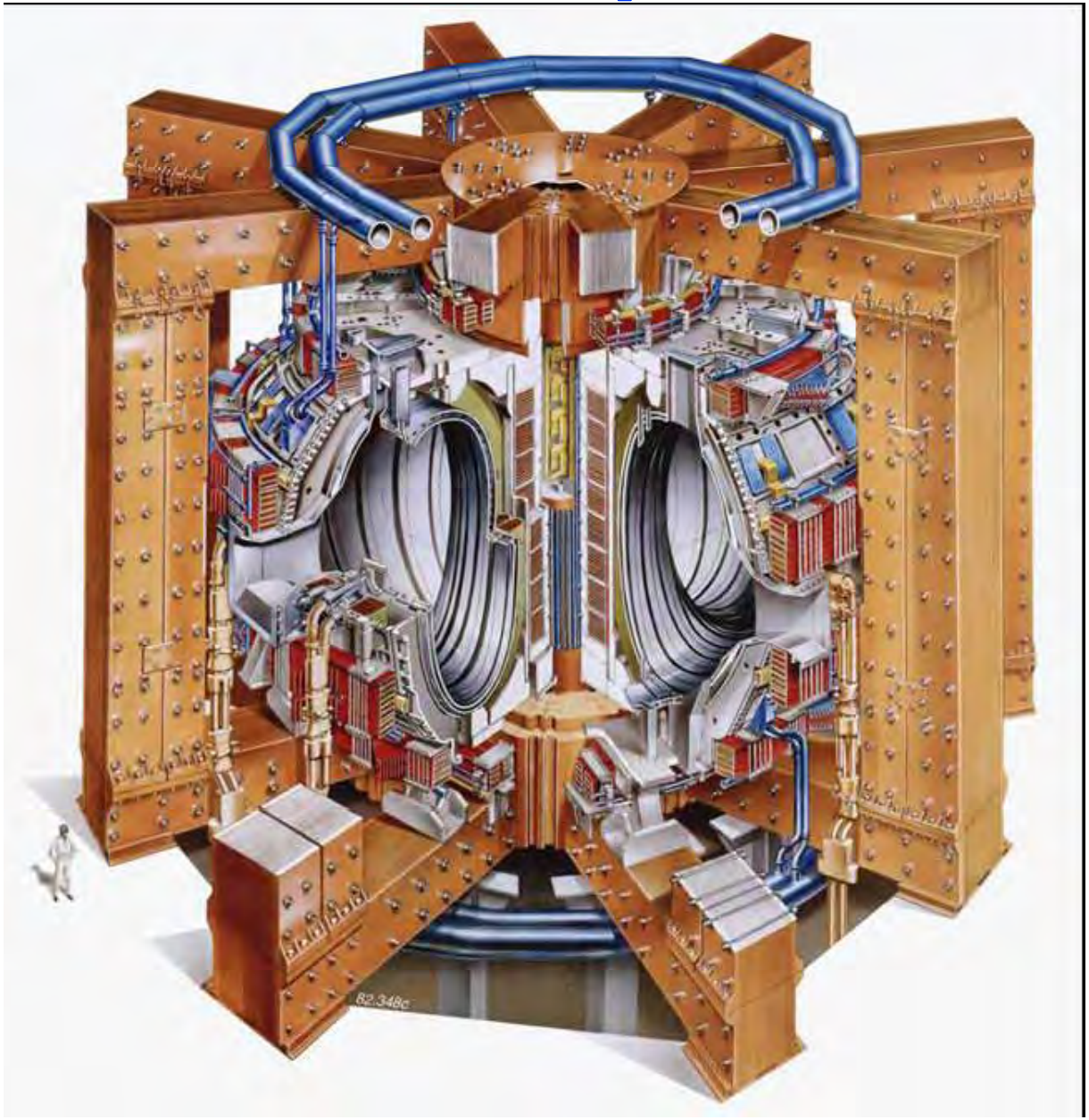
Source: Irish Times June 2005

Fuzija

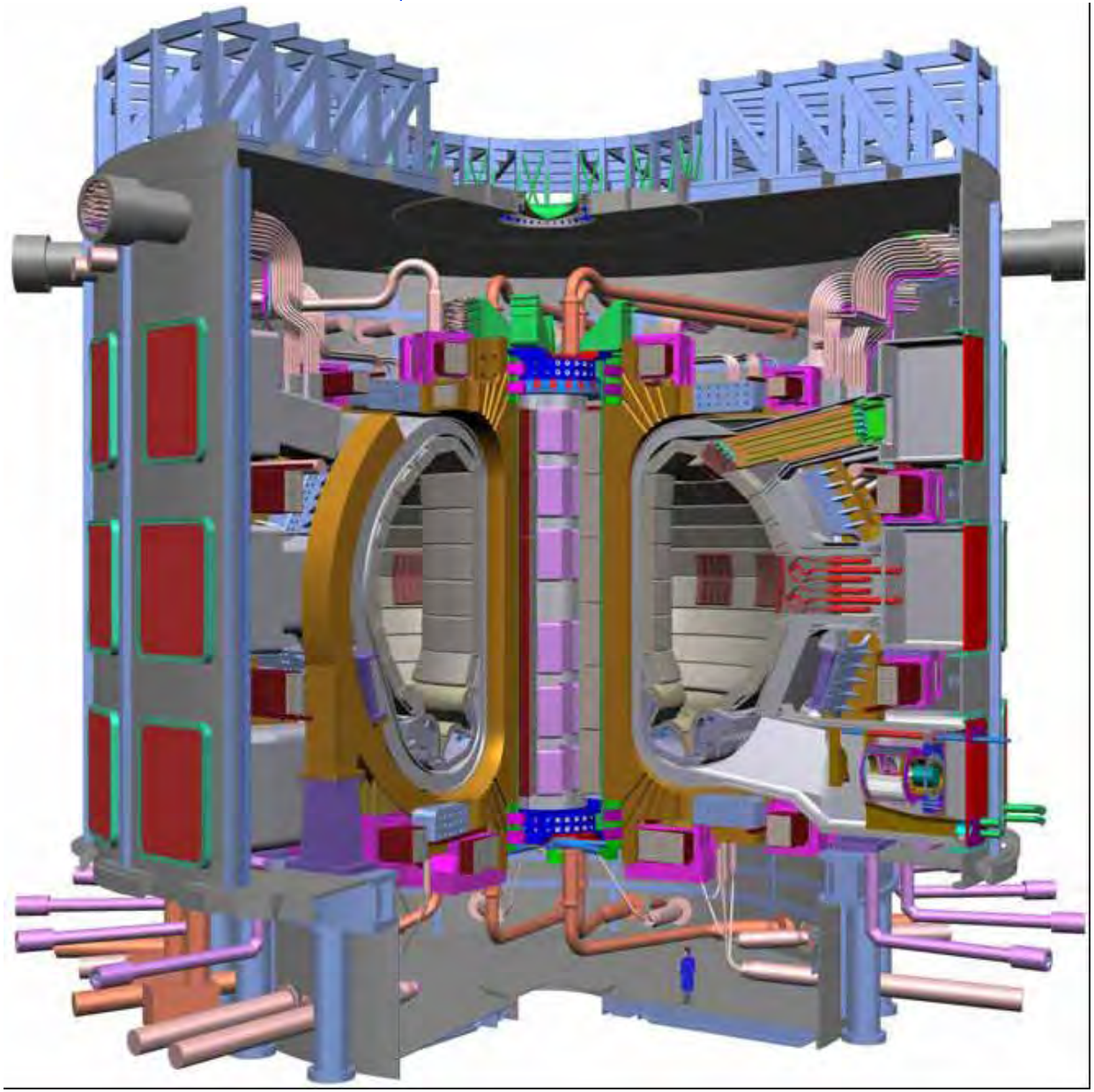
Fuzija

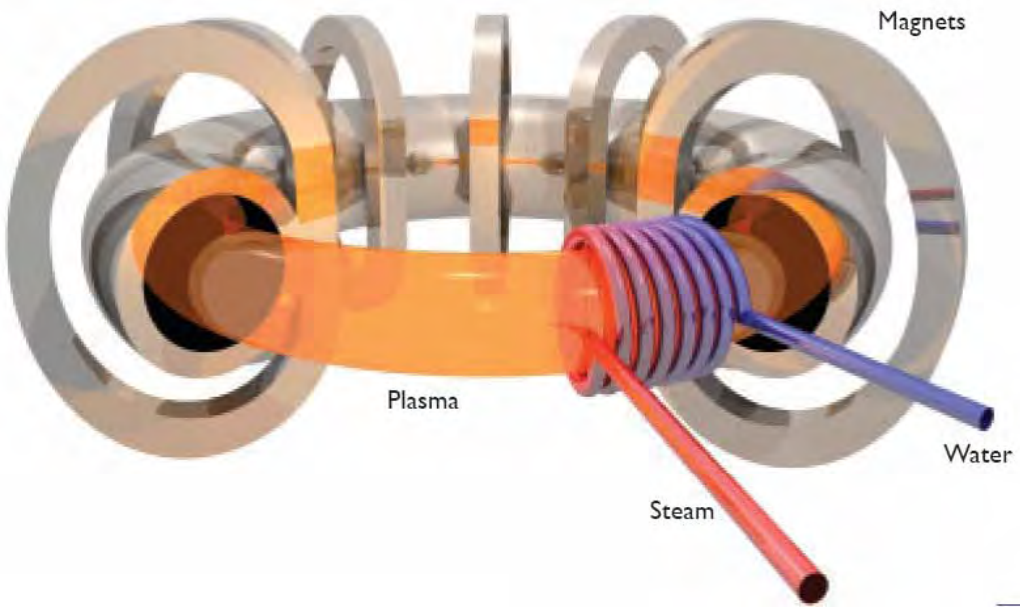
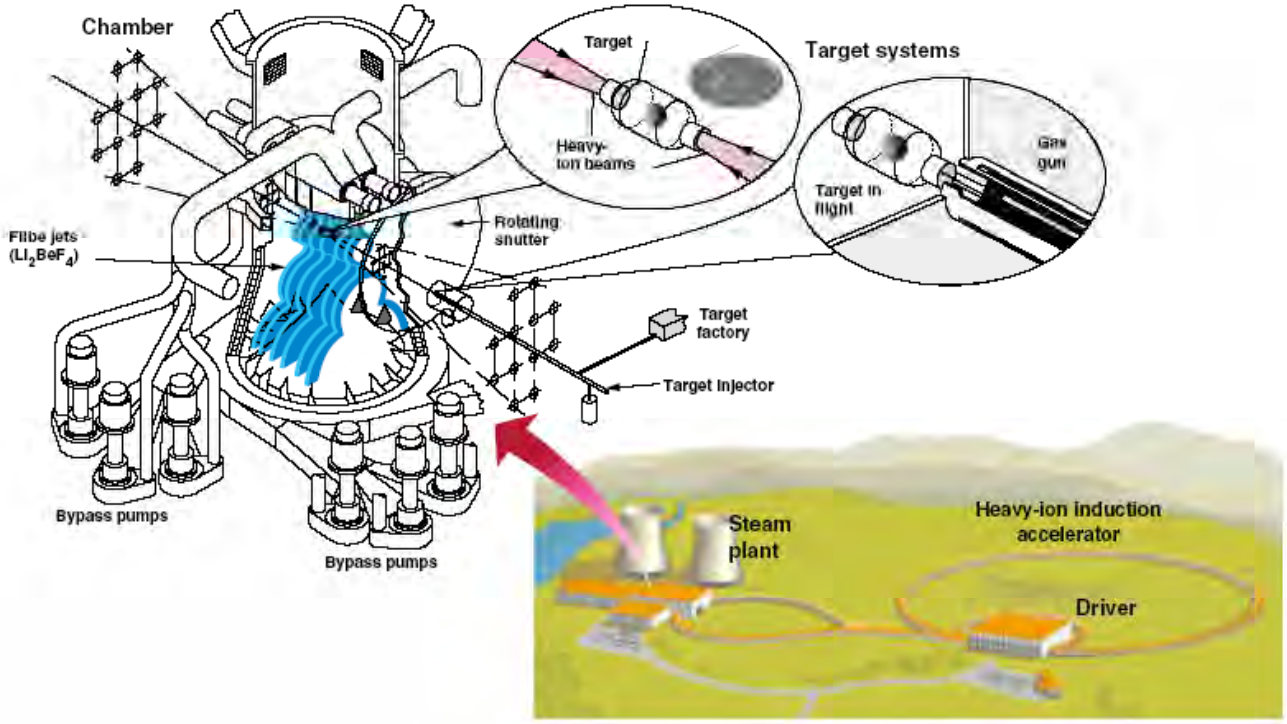
- **Potencijalne prednosti**
  - **Gotovo neograničene količine goriva**
    - **Deuterij u vodi**
    - **Tricij iz litija (dio procesa)**
  - **Inherentno sigurni**
  - **Mala količina dugoživućeg radioaktivnog otpada (aktivacija), problem je tricij**
  - **Nema mogućnosti proliferacije**
- **Međunarodna suradnja – ITER, cilj postići 500 MW tijekom 500 do 2500 s**
- **Komercijalizacija tek poslije 2050**
- **Ne očekuje se značajniji doprinos prije druge polovine stoljeća**
- **Moguća razna iznenađenja, male zemlje ?**

JET (Joint European Torus)



ITER (International Thermonuclear Experimental Reactor)



Fusion power	500 MW
Heat flux at 1st wall	0.57 MW/m2
Confinement time	≥ 300 s
Plasma radius (torus)	6.2 m
Plasma radius (cross)	2.0 m
Plasma current (ind)	15 MA
Toroidal field at 6.2 m	5.3 T
Plasma volume	837 m3
Plasma area	678 m2

Fuzijska elektrana?